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# A FIRST COURSE OF
# PHYSICAL LABORATORY PRACTICE

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TILDEN FOUNDATIONS
1901

# PREFACE TO THE SECOND EDITION.

A few errors kindly pointed out by Reviewers, or by Teachers who have used the book, have been corrected in this Edition, which otherwise remains the same.

During the two years that have elapsed since its first publication, several Schools in this country have been equipped with Physical Laboratories, and it is coming to be generally recognised that the training thus provided affords the best foundation for a scientific education.

There seems, however, to be some danger that the desire of Teachers to secure more exact experimental results may lead them at much too early a stage in the instruction to adopt indirect methods, or to discuss details in a way that obscures the main issue, or even to introduce into the course experiments of which the theory is quite beyond the pupil's grasp, simply because the manipulation happens to be easy and the subject important.

It has been my special effort to select such experiments as shall give a good mental grip of the point to be illustrated, and to confine the attention to matters that I have found can be fairly mastered by boys from fourteen to sixteen years of age. For this reason the book is called a First Course.

A. M. WORTHINGTON.

H.M. Dockyard,
Portsmouth, *5th April* 1888.

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# INTRODUCTION.

THIS book, which is intended to supersede a little volume published a few years ago, is written with the object of encouraging the teaching of Physics in schools, especially by means of laboratory work, in which the pupil performs his own experiments. It embodies the Experimental Course which has been found suitable for *beginners* at Clifton College, where the author has had several years' experience in conducting large laboratory classes of as many as thirty pupils at a time.

In the very valuable report of the United States Government Bureau of Education, edited by Mr. C. K. Wead of the University of Michigan, and published in 1884, there occurs among the answers to a question as to the desirability and feasibility of laboratory work in schools, one which urges that it is objectionable "to put students to experimental work when unqualified for it, and with inadequate means. Thus habits of slovenly experimenting and inconsequent induction are formed, or the student is disgusted with the unsatisfactory nature of the whole thing. Especially is a loose way of experimenting with cheap apparatus, and obtaining only the remotest approximation in results—results which would not of themselves even suggest the principle or law—very much to be deprecated." I think it not unlikely that an objection of this kind may be felt by some of our own scientific men who may be without personal experience in teaching the elementary portions of the subject to young students, and therefore take this opportunity of saying a few words on the point.

Our experience at Clifton has shown that experiments can be selected which shall lead to quantitative results quite sufficiently accurate to suggest or confirm the correctness of the principle involved without taxing too much the patience or the intelligence of the young experimenter. And we have found that, so far from being disgusted with the unsatisfactory nature of the experiment, he is generally encouraged by feeling that an accurate result is within his reach if he takes sufficient pains. To be sure, his own standard of accuracy is a low one in comparison with that of a trained Physicist, but this is only a symptom of his undeveloped condition, and as he becomes more practised, his standard improves of itself. It is precisely thus that the standard of precision in all attainments grows gradually with practice and increasing mental power. How many stages lie [illegible] the games of young children and the same games as played by men! Such a laboratory course as I advocate recognises the low standard of particular faculties, and gives them an early opportunity of natural growth. No doubt it would be prejudicial to keep a pupil very long at work in which the highest standard attainable was kept out of sight. For this reason this preliminary laboratory work at Clifton is confined to boys in the Middle School, *i.e.* of about the ages of fourteen to seventeen, after which point it either ceases or is exchanged for more exact work, modelled more or less on the teaching in the University laboratories.

But there is another aspect of this work to which I would call attention. It should not, I think, at first be the aim of the teacher to show his pupils how measures of Physical Constants may be *most accurately* made, so much as to give them a clear idea as to what such measures *mean,*—to give them, in fact, a thoroughly intelligent conception of what is to be aimed at. And for this reason the methods of measurement should at first be, if possible, such as most naturally suggest themselves to the mind of the learner, or such as are least encumbered with secondary considerations, and all subordinate "corrections" likely to obscure the main issue should at first be avoided, while at the same time the pupil should make the measurement himself.

In this respect I conceive that the teaching of younger should differ from that of older pupils who have already attained sufficient grasp and patience to face with pleasure the complicated considerations essential to the more accurate measurements, though, even with senior students, what may be called "instructive" rather than "accurate" methods of measurement may sometimes be selected with advantage. For among the ultimate ends of our science-teaching, to the great majority of pupils, who are not likely to become specialists, we must surely reckon as very important the interest in natural phenomena that results from mastering some principles of Nature, and the resources of intellectual enjoyment which such interest throws open in after life.

Of the educational value of the systematic, practical study of Physics, as here advocated, those who have watched it at Clifton, and have observed its popularity with the boys, have little doubt. It is undertaken there, like all the scientific teaching, not with a view of training up Physicists, but with the object of evoking in the boys a genuine and generous interest in natural phenomena, and of training them to habits of patient and conscientious study; and those of us who have devoted themselves more particularly to the Physical Sciences are confident that the serious interest thus early aroused in a large number is the best guarantee of future excellence in the few who may afterwards become specialists.

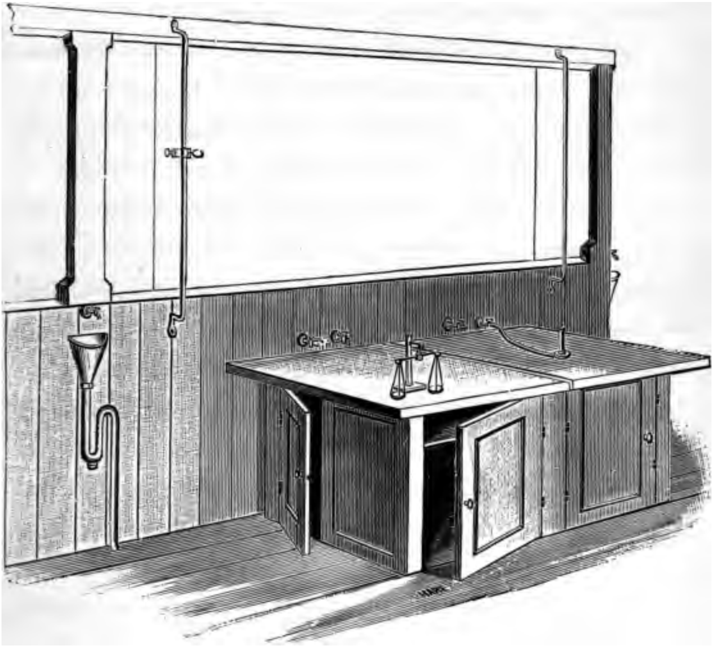
To pass to matters of detail :—I have found that it is desirable, when setting a young student to perform an experiment for himself, to give him something more than a bald description of what is to be done. It is necessary in many cases to point out clearly what the experiment is designed to teach, and often for this purpose to summarise information already acquired, so that the significance of the experiment and its results may be more fully perceived; and unless this be carefully done, the work loses much both of its value and interest. For this reason the experimental practice should always be accompanied or preceded by experimental lectures, or by a carefully written comment on the experiment that the student is himself to perform. And I have found that the former will not always supply the place of the latter, since it is not always possible to work the two systems of instruction hand in hand. Exigencies of school arrangement will sometimes prevent the experimental classes from consisting of quite the same individuals as the lecture classes, and it often happens that the lectures will get ahead of the experimental work, or the experiments of the lectures. Consequently the commentary that accompanies the experiments which the pupil is to perform should repeat (it may be in a condensed form) the information that is given in the lecture.

In the course, therefore, which follows, it will be found that the remarks by which the experiments are introduced or explained often assume the character of a written lecture; the object which was in my mind being to afford to the student all the requisite materials for teaching himself.

At Clifton the senior boys take home their rough notes of experiments performed, while the juniors write out the fair copy before leaving the laboratory—always in pencil, no ink being allowed in the room.

The boys work in pairs, an arrangement found on the whole quite satisfactory, and each pair works quite independently of the rest, some getting on much faster than others. This independence is an advantage, not only because it renders it unnecessary to keep apparatus enough for all to be doing the same thing at once, but also because it makes each boy feel that his progress is in his own hands.

The laboratory is a large well-lighted room, 28 ft. by 22 ft., fitted with suitable tables, cupboards, gas, and water. The nature of the fittings may be gathered from the cut on the opposite page, which shows a work-table for four boys (two pairs). Below each half of the table is a cupboard with a shelf containing the apparatus in most frequent use. For the sake of light, these cupboards are not separated by any internal partition. At the back is a long narrow cupboard running the whole length of the table, with a shelf and a door at each end; in this are kept the note-books or special apparatus in current use. On one table is seen the moveable staff for holding the balance, on the other, a burner connected with one of the pear-shaped gas heads. The top is of well-seasoned deal, 2 in. thick, with a square-cut edge, and projects 5 in. over the cupboards. The total length of the table is 6 ft., depth 3 ft., and height 2 ft. 10 in., and the two halves of the top are separated by a moveable strip of wood.



Near each half of the table is seen a water-tap and small sink, provided with a trap in the escape-pipe for the recovery of small objects which may have been accidentally dropped down. Behind the table is seen a strong wooden partition, open at the top, separating it from similar tables at the other side. In front of this are fixed, as shown, tall iron upright rods of the same thickness as the rods of the retort stands, and to which the retort stand clips can be fixed, at any desired height, for holding pendulums, torsion wires, etc. For other tables, these uprights are fixed to the walls of the room.

It is convenient to have the front cupboards fitted with snap-locks, all of which can be opened by the same key. In order to secure complete tidiness in the cupboards, I have found it essential that every piece of apparatus should have its place duly marked with a label in the cupboard, and to insist that each piece shall be put back exactly in its right place. Three or four minutes before the end of the lesson the word is given to put away the apparatus, and either before or after the boys have gone, the master, walking round and looking at the open cupboards, can tell at a glance whether everything is in its place. The cupboard doors are snapped to, and five minutes after the cessation of work he can walk out of the room, assured that everything is in perfect order *for the next* lesson. The apparatus not in immediate use is kept in suitable cupboards on the walls of the room. A complete list of all that is required for the experiments of this course will be found at the end of the book.

A few words on the question of cost of this kind of laboratory work may not be out of place.

The tables that I have described cost £3, 3s. each, and the total cost of the interior fittings of the Clifton laboratory, for a class of thirty boys, including the tables, wall-cupboards, blackboard, a stone sink, central partition, gas and water fittings, may be put at very nearly £70. The original outlay in apparatus four years ago was £40, and the annual cost of working, supplying material, and replacing breakages, has for the last three years been £12, 10s. per annum.

With respect to the time required for the performance of the experiments described in the course, the following details may be useful; the information given refers to pupils of ordinary intelligence and industry.

Part I. (Mensuration) requires a little more than one school term of thirteen lessons of one hour each, though it is sometimes finished in one term.

Parts I., II., and III. (Mensuration, Hydrostatics, and Barometer and Boyle's Law) can be accomplished in two such terms.

Part IV. (Mechanics, including (1) Levers and Parallelogram of Forces, (2) Centre of Gravity, (3) Friction and Inclined Plane, (4) Friction of Cords and Use of Pulleys) takes less than one term of twenty-six hour lessons.

Part V. (Elasticity and the law of the Simple Pendulum) takes less than one term of twenty-six hours.

Part VI. (Heat) requires about one term of twenty-six hours.

Part VII. (Magnetism) takes rather less than one term of twenty-six hours.

Part VIII. (Statical Electricity) takes one term of twenty-six hours.

Part IX. (Current Electricity) takes about one term of twenty-six hours.

The order in which the sections are taken by the pupil need not necessarily be that in which they are arranged in the book, but it is recommended that the first three sections be imperative on all beginners, and that they be taken in order.

An acquaintance with vulgar and decimal fractions and simple proportion, in Arithmetic, and with at least the first book of Euclid, is requisite.

*The following Rules to be observed by Boys working in the Laboratory have been found convenient.*

## RULES.

1. Read all about the experiment, so as to have a clear idea of what you are going to do before you begin.

2. Remove all apparatus from the table to its proper place *as soon as it is done with.*

3. The form in which the experiment is to be recorded should be got ready beforehand, so that as soon as an observation is made it can be recorded in its right place in the form.

4. The numbers thus recorded in pencil in the rough note-book must not be the result of additions or subtractions done in the head, but the numbers on which such calculations, however short, depend.

5. Even when the measure made by the second observer of a pair agrees with that made by the first, both must be recorded.

6. Make all the necessary observations before proceeding to any calculation.

7. Books, etc., not wanted during the lesson must not be placed on the tables.

8. All waste-paper, etc., to be put in the waste-baskets.

9. All breakages to be reported at once, and put down in the breakage-book.

10. No talking is allowed, except in a low voice to your partner.

11. Before leaving the room, examine your cupboard to see that everything is in its place.

# PART I.

# MENSURATION

(23 *Experiments.*)

## PART I.

# MENSURATION.

**Physics** is essentially the science of measurements; and since in all sciences we require constantly to measure lengths, areas, volumes, times, masses, quantities of electricity and of heat, etc., the first care of the student must be to learn how to make accurate measures of such quantities. Much of this may be learned without the use of very elaborate or costly apparatus, for the principles which underlie the use of an instrument are independent of the excellence of the workmanship expended on it, and are often best illustrated in the simplest forms of apparatus.

The first thing that will be required of you in this Practical Course is the accurate measurement of lengths.

**The Metre Measure.**—You are provided with two measures or rules, the longer of which is called a *metre* and the shorter (which is often more convenient to use) is half a metre. This metre, you will notice, is rather more than a yard long, being, in fact, very nearly one yard and one-eleventh. It has been chosen as the unit of length for all scientific measures, and is used on the Continent of Europe for the measurement of cloths, ribbons, the length of roads, etc., and, in fact, wherever we should use a yard measure.

When this length of the metre was first agreed upon it was believed to be exactly one ten-millionth of a quarter of the earth's circumference measured from pole to pole through Paris, and a bar of platinum—one of the most indestructible of metals—was made to represent this length when at a temperature of ice-cold water, and was deposited in Paris to serve as a standard for the future, from which other metre measures could be made. Subsequent surveys of the earth showed that the length of this bar was not exactly what it professed to be; but as there is no particular virtue in one ten-millionth of a quarter of the earth's circumference, the bar is still regarded as the standard metre, and from it all other metres have been directly or indirectly copied.

If you look at the subdivisions on your rule, you will see that it is divided as in the figure (Fig. 1).

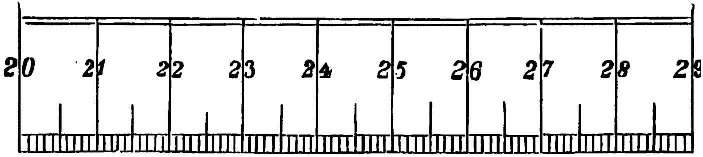


FIG. 1.

**Subdivisions of the Metre.**—The longest strokes, where the figures 20, 30, . . . occur, mark the division of the metre into *tenths*.

The next longest mark the *hundredths* of a metre, and the smallest divisions of all are each *one-thousandth* of the whole length.

For the names of these subdivisions words derived from the Latin numerals are used. Thus

One tenth of a metre is called a *decimetre* from *decem* = ten.
One hundredth „ „ *centimetre* „ *centum* = a hundred.
One thousandth, „ „ *millimetre* „ *mille* = a thousand.

**Multiples of the Metre.**—Similarly, for *Multiples* of the metre, names derived from the Greek numerals are used. Thus

10 metres are called a *dekametre* from Greek *deka* = ten.
100 „ „ *hectometre* „ „ *hekaton* = a hundred.
1000 „ „ *kilometre* „ „ *chilioi* = a thousand.

**English Equivalents.**—The English equivalents of some of these are given in the following table:—

| Approximately | | Very exactly | |
|---|---|---|---|
| 1 metre | = $1\frac{1}{11}$ yards. | 1 metre | = 1·0936 yards. |
| 1 inch | = 25·4 millimetres. | 1 inch | = 25·3995 millimetres. |
| 8 kilometres | = 5 miles. | 1 kilometre | = 0·62138 miles. |

**Abbreviations.**—

*Metre* is commonly abbreviated into "m."
*Decimetre* „ „ „ "decim."
*Centimetre* „ „ „ "cm."
*Millimetre* „ „ „ "mm."

**Convenience of the Metric System.**—The advantage of a decimal system of subdivisions and multiples is seen not only when we wish to change the unit from one denomination into another, but even in the manner of recording the quantity. Thus, if using our English system we measure a length and find it to be (say) 12 yds. 2 feet 7 in., we have in writing it down to write headings "yards," "feet," and "inches." But in the metric system, instead of writing (say)

metres decim. cm. mm.
20 5 4 1 we may at once write it as

m.
20·541

decim.
or 205·41

cm.
or 2054·1

mm.
or 20541·

**Estimation of Tenths of a Millimetre.**—It is often necessary to measure a length more accurately than to the nearest millimetre, and it is not difficult to *imagine* each millimetre divided into 10 equal parts, and to estimate with considerable accuracy that the length which is being measured is so many centimetres, so many millimetres, and so many tenths of millimetres.

The following is an example of the estimation of tenths of a millimetre in this way :—

**Example.**—On the scale shown in the accompanying figure the distance

0A = 1 cm. 3 mm. and 8 tenths of a millimetre, or 1·38 cm.
0B = 2 cm. 3 mm. and 5 tenths of a millimetre, or 2·35 cm.
0C = 4 cm. 9 mm. and 0 tenths of a millimetre, or 4·90 cm.

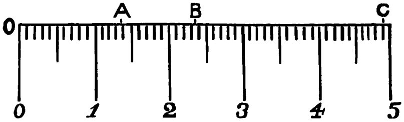
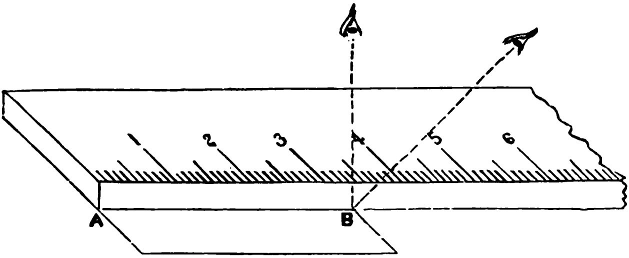


FIG. 2.

For lengths less than one metre it is usual to make the centimetre the unit.

**Method of Using the Scale.**—In order to use your metre rules to measure very accurately the distance between two points, several precautions must be taken. Fig. 3 illustrates a *bad* way of using the rule to measure the distance between two points A and B.



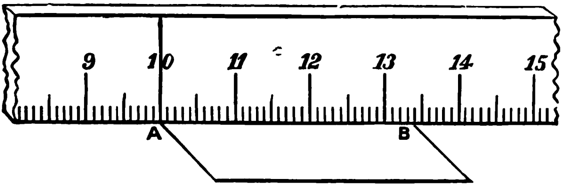
BAD WAY OF USING THE SCALE.

Fig. 3.

Here the thickness of the rule causes an error, if the eye does not happen to be held exactly over the point B.

Also the end of the scale is seldom bevelled off quite square, or so accurately cut that the last division can be trusted.

Both errors are avoided by placing the rule on its edge as in Fig. 4, and starting, not from the end, but from (say) the 10th centimetre.



GOOD WAY OF USING THE SCALE.

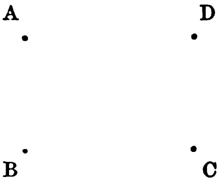
Fig. 4.

EXERCISE 1.—*Measure the distances AB, BC, CD, DA, AC, DB, in the diagram given you, estimating to tenths of a millimetre.*

*Instructions.*—The following example of a record of a similar exercise is given to show how to record the result:—

### EXERCISE 1.

### Direct Measurement of Distances in a given Diagram.



The diagram was such as is represented in the rough sketch of the figure.

cm.
AB = 3·66
BC = 3·69
CD = 3·41
DA = 3·60
AC = 3·08
DB = 3·81

Observe that the reading 3·60 cm. does not mean quite the same thing as 3·6 cm. The former shows that tenths of a millimetre could be estimated, and that you observed that the length was more nearly 3·60 cm. than 3·59 cm. or 3·61 cm. The latter means that tenths of a millimetre were not taken into account. Consequently, unless you have carefully estimated the tenths of a millimetre, you have no right to write 3·60 cm., but must write 3·6 cm.

**The Measurement of Curved Lines.**—The length of a curved line drawn on any surface may often be measured in various ways.

Such a curve as ABC of the figure (Fig. 5) may be regarded as made up of a succession of small straight portions as indicated by the cross lines, and the length of the whole must be very nearly equal to the sum of the lengths of these short straight pieces. Hence the length of such a curve can be found with considerable accuracy by means of a thin flexible thread, which can be stretched along the curve in a series of short straight portions by the fingers, as in Fig. 6.

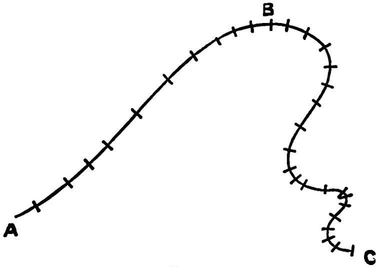


Fig. 5.

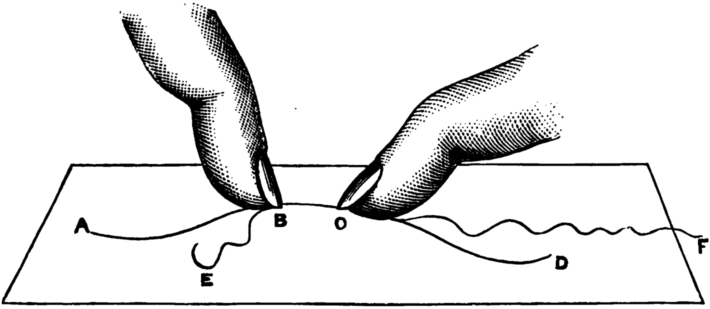


Fig. 6.

**BC** is the part of the curve being measured.

**AB** is the part that has been measured.

**EB** is the part of the thread, now left loose, which was used up in measuring AB.

**CD** is the part of the curve still to be measured.

**CF** is the remainder of the thread, more than sufficient in length to measure it.

The length of thread used in this way must then be measured along the metre measure.

EXERCISE 2.—*Measure and record the length of the curves given in the diagram.*

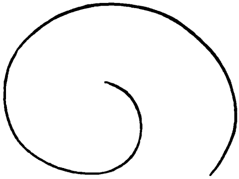


FIG. 7.

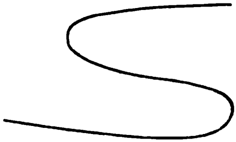


FIG. 8.

**In some cases** the length of the curved outline of a body may be found by rolling it. Thus, if a mark is made on the ground where a wheel rests, and a mark be also made on the lowest part of the wheel, then if the wheel be rolled once over till the same mark is again at the lowest point, the distance between its new position on the ground and the old position is equal to the circumference of the wheel.

EXERCISE 3.—*Find, by rolling along a straight line drawn on a piece of paper, the circumference of* (1) *a Penny,* (2) *a Shilling.*

*Instructions.*—It is sometimes difficult to prevent the coin from slipping along the paper, and it is necessary to repeat and record each measure at least twice to be sure that no slipping has taken place.

**The Opisometer.**—Conversely, when we know the circumference of a wheel, and also how many turns it has made, we can tell how far it has travelled.

A very convenient little instrument for measuring the *lengths* of curves, or the lengths of roads and lines on a map, is based on this principle, and is figured in the accompanying diagram (Fig. 9).

It consists of a little frame fastened on to the end of a penholder, and carrying the little wheel A, which is armed with minute teeth, to prevent its sliding over the paper with out turning.

As the wheel turns, it at the same time advances along the axis BB′, which is fixed in the frame and cut with a screw thread of fine pitch.

At starting, the wheel is at the end B, and after it has been run along the line whose length is to be measured, it is lifted off the paper and run *backwards* along the measure till it gets back to the end B at which it started, when it will turn no longer; the pointer at the end B then shows on the scale the length of the line that has been traversed.

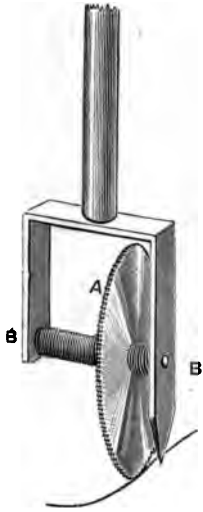


Fig. 9.

Exercise 4.—*Measure with the "Wheel-Measure," or "Opisometer," the lengths of the lines of Exercise* 2.

*Instructions.*—Record thus—

Exercise 4.

**Measurement of the Length of Curved Lines with a Wheel-Measurer.**

**The curves measured were those of Exercise 2.**

1st curve. Length as measured with thread . . . . cm.
,, ,, ,, wheel . . . . cm.
2nd curve. Length as measured with thread . . . . cm.
,, ,, ,, wheel . . . . cm.

**Indirect Measurement of Curved Lines.**—In the case of certain geometrical figures the length of a curved line can be calculated from the length of certain straight lines, *e.g* the circumference of a circle is known when we know its diameter.

EXERCISE 5.—*To find how often the circumference of a circle contains the diameter.*

*Instructions.*—Describe with a pair of compasses on a sheet of paper a circle of at least 8 cm. radius, taking care that the pen or pencil which traces out the circumference makes a very thin well-defined line. Measure very carefully, and record in cm., the diameter of the circle. Then measure the circumference, either with a thread as in Exercise 2, or with a wheel-measurer as in Exercise 4, and record the result in cm.

Now divide the latter result by the former, carrying on the division as far as the 4th significant figure. Let the record be made on the following model:—

EXERCISE 5.

**To find how often the circumference of a circle contains the diameter**

Diameter of circle = . . . . cm.

Circumference as measured with . . . . = . . . . cm.

$$\therefore \frac{\text{Circumference}}{\text{Diameter}} = \frac{\ldots}{\ldots} = \ldots .$$

Now repeat the same process with two other circles of different sizes, and record the result in the same way. Then take the average or mean of the three results. If your measures are carefully made, you will get *very nearly* the same result in each case.

**The Symbol π.**—If you could draw the circle and make the measurements with perfect accuracy, you would get the value 3·14159 . . . . . which can be shown by geometry to be the true value of the ratio of the circumference of a circle to its diameter.

This ratio is for brevity expressed by the Greek letter $\pi$. Thus we say that the circumference of a circle is $\pi$ times its diameter, or circumference = diam. × $\pi$,
instead of circumference = diam. × 3·14159 . . . . .

Since $3\frac{1}{7} = 3\cdot\dot{1}4285\dot{7}$, which only differs from $\pi$ by 1 in the third place of decimals, *i.e.* by less than one three-thousandth part of the whole, we shall in future, in this course, regard $\pi$ as being equal to $3\frac{1}{7}$, since our calculations will be thereby much facilitated, while the error introduced will be in general inappreciable, for we shall not usually be able to find the value of any quantity within narrower limits than $\frac{1}{1000}$ of its total value.

**Approximation in Arithmetical Results.**—For this reason also, whenever we have to calculate an average or any other quantity, we need not as a rule calculate out the result beyond the *4th significant figure*, since by omitting the rest we cannot be making an error of as much as one-thousandth of the whole.

**Example 1.**—The diameter of a circle is 82·34 cm.: find the circumference.

Circumference = 82·34 cm. × $3\frac{1}{7}$
3 × 82·34 cm. = 247·02 cm.
$^1$ of 82·34 cm. = 11·76 . . . .
∴ Circumference = 258·8 cm. (very nearly).
(All figures beyond this are unnecessary.)

**Example 2.**—The circumference of a circle is ·2 cm.: find the diameter.

Diameter = circumference ÷ $\pi$
,, = ·2 cm. ÷ $3\frac{1}{7}$
,, = ·2 cm. × $\frac{7}{22}$
,, = $\cdot\frac{7}{11}$ cm.
,, = ·06363 cm.
*(All figures* beyond this are unnecessary.)

**Indirect Measurement of the Diameter of a Sphere.**—The diameter of a ball may be found indirectly by measuring its circumference, which may be most accurately done by rolling it over on the table till a mark which touched the table at starting again touches it. The mark should be a fine line, part of a great circle (as shown in Fig. 10); a piece of white paper should be laid on the table to roll the ball on, and the face of a block may be used to guide the ball as it is rolled.

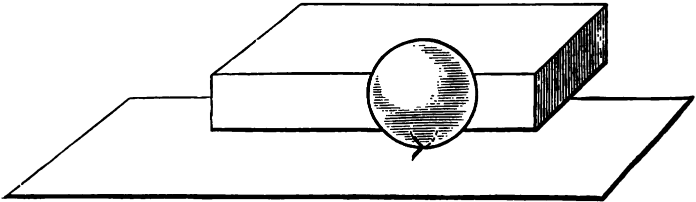


FIG. 10.

EXERCISE 6.—*Measure in this way the circumference, and thence deduce the diameter of the wooden sphere in your cupboard.*

**To Measure the diameter of the sphere directly,** we may place it between two square-cut blocks (as in Fig. 11) whose faces are pressed up against a third, and then measure the distance across the blocks.

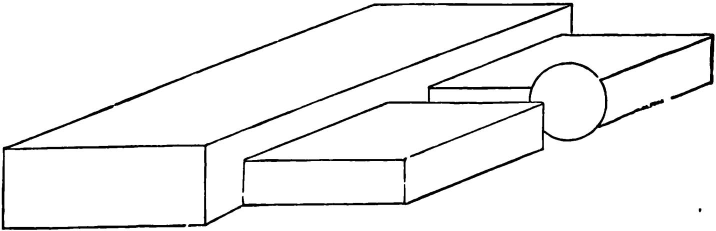


FIG. 11.

The kinds of error to which a measurement made in this way is liable are illustrated in the accompanying diagrams:—

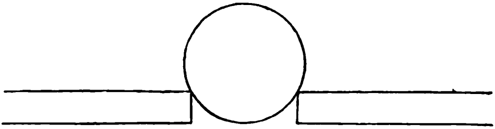


FIG. 12.—Here the blocks used are too thin

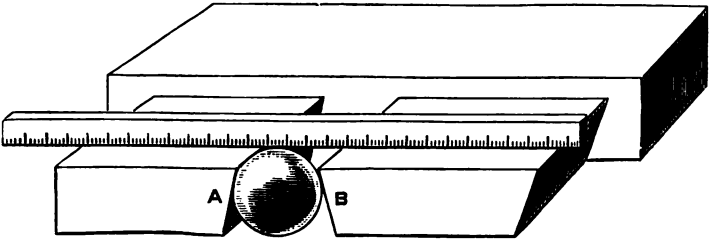


FIG. 13.—Here the blocks are thick enough, but are not accurately cut, so that the distance across at the top is not the same as the distance across at the level AB.

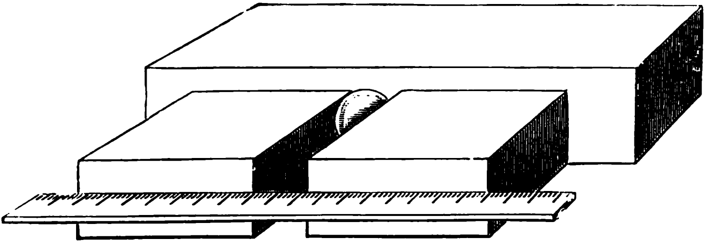


FIG. 14.—Here the measure is placed at the right level, but the ball being at the other end of the blocks, the distance across where the measure is placed will not be equal to the diameter of the ball if the blocks are inaccurately cut.

All these errors may be avoided by placing the ball close to the end *where the* measurement is to be made, as in

Figure 11, then slipping it out and measuring across as in Figure 14, *just where the ball has been.* If the faces of the two blocks between which the sphere is placed are nearly parallel, they will touch the sphere *very nearly* at the ends of its greatest diameter.

It is by attention to points of this kind that you will be able to obtain accurate results. After you have made many measurements of many different kinds, you will know by experience what sort of errors to look out for, and how to avoid them.

EXERCISE 7.—*Measure directly between blocks the diameter of the same ball that you used in Experiment* 6.

**Remark.**—It is to be observed that even though you may find that you can measure the diameter directly with greater accuracy than you can measure the circumference, yet the value of the diameter as deduced from the circumference may be more correct, for any error made in the measurement of the circumference is divided by $3\frac{1}{7}$ in deducing the diameter.

## THE METRIC SYSTEM OF WEIGHTS.

Before proceeding to the measurements of areas and volumes, it will be convenient to explain the system of weights in use among scientific men.

The unit weight that has been agreed upon is called the gramme or gram, and is the weight of a cubic centimetre of cold water, *i.e.* of as much water as would fill such a box as that shown in the figure, each of whose interior edges is 1 cm. long.

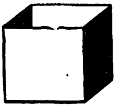


Fig. 15.

As with the measures of length, the decimal system is adopted; names derived from the Latin being used for subdivisions, names derived from the Greek for multiples.

Table of Weights.

$\frac{1}{1000}$ of a gram = ·001 gr. is called one milligram.
$\frac{1}{100}$ " = ·01 gr. " " centigram.
$\frac{1}{10}$ " = ·1 gr. " " decigram.
1 gram is called 1 gram.
10 grams are called one decagram (a term not much used).
100 " " " hectogram.
1000 " " " kilogram.

The English equivalents are shown in the following table :—

1 gram = 15·4323 grains.
1 oz. (Avoirdupois) = 28·3495 grams.
1 kilogram = 2·20462 lbs. (Avoirdupois).
= $2\frac{1}{5}$ lbs. (nearly).

## RULES TO BE OBSERVED IN WEIGHING.

1. The scales should first be examined to see that they are in equilibrium to begin with, and if not, a counterpoise should be added to the lighter pan.

2. It is not necessary or desirable to wait till the balance is at rest; when it swings evenly on either side the equilibrium is correct.

3. The object to be weighed should be placed in the left-hand pan, the weights in the right.

4. After the largest weight that can be used has been put on the pan, the rest must be tried *in order, missing none.* It is only by attention to this rule that you can learn to weigh quickly.

5. The weights must never be anywhere but in the pan, or in their place in the box.

6. When the weighing is correct, write down the result by seeing what weights are missing from their places in the box; then check this result as you put them back into their places.

7. The small weights must never be handled with the fingers, which might cause them to rust, but only with the tweezers.

8. Never use the weights to make a simple counterpoise, but always shot, or shot and paper.

## ON THE MEASUREMENT OF AREAS.

**The Unit of Area** that we shall use is the square centimetre (Fig. 16), *i.e.* the area of a square of the size of the figure, each of whose edges is 1 cm.

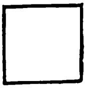


Fig. 16.

To find the area of any surface is to find how many such unit areas are required to cover it.

The area of a rectangle (see Fig. 17) is evidently obtained by multiplying the number of cm. in the length by the number in the breadth, for the former tells us how many square cm. and parts thereof can be laid along one side forming a strip 1 cm. wide, such as AA in the figure, while the latter tells us how many such rows and parts thereof there will be.

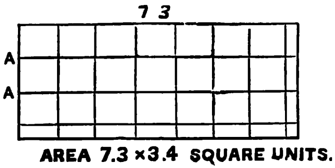


Fig. 17.

**To find the Area of an Oblique Parallelogram.**— Since by Euclid, Bk. I. Prop. 35, parallelograms standing on the *same base and between* the same parallels are equal,

∴ the area of the oblique parallelogram ABCD is the same as that of the rectangle BCEF.

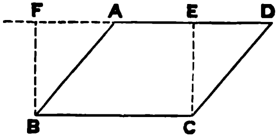


FIG. 18.

Now the line EC, which represents the shortest distance between the side BC, which we have chosen as the base of the parallelogram ABCD, and the *direction* of the opposite side, is called the *altitude* of the parallelogram ABCD. Hence we get the following rule:—

To find the number of square units in any parallelogram,—

*Multiply the number of units of length in the base by the number of units of length in the altitude;*

*Or*, less correctly expressed,

*To find the area of a parallelogram, multiply the base by the altitude.*

**To find the Area of a Triangle.**—By Euclid, Bk. I. Prop. 41, the area of a triangle ABC of either figure (Figs. 19 and 20) is half that of the parallelogram BCDE, which stands upon the same base and between the same parallels.

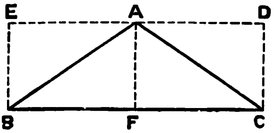


FIG. 19.

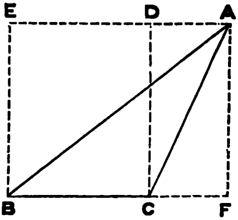


FIG. 20

Therefore the area of ABC = $\frac{1}{2}$ BC × DC.

Now DC is equal to the line AF, which is the shortest distance from the vertex A of the triangle to the direction of the side BC, which we have chosen as base, and is called the *altitude* of the triangle.

Hence the following rule:—

To find the number of square cm. in a triangle—

*Choose one side as base; from the opposite angle let fall a perpendicular on to this base or this base produced; multiply the number of cm. in the base by the number of cm. in the perpendicular, and halve the result;*

*Or*, more briefly, but less correctly expressed—

*Area of a triangle* = $\frac{1}{2}$ *base* × *altitude.*

It is evident that we might choose any of the three sides as base, and that by drawing the appropriate *altitude* we should obtain the same result in each case.

EXERCISE 8.—*Draw by means of rule and compasses a triangle whose sides are about* 20 *cm.*, 15 *cm., and* 10 *cm. long respectively. Then measure its area, choosing each side in turn as base.*

*N.B.*—In drawing the triangle to be measured, a very finely-pointed pencil should be used, and the lines should cross at the angles, since the intersection of two lines marks a point much better than a dot, which it is difficult to make both small and distinct.

*Instructions.*—Let your record contain a "sketch" of the triangle on a smaller scale, with the perpendiculars which it was *necessary to draw.*

The following is an example of a record of a similar exercise :—

### EXERCISE 8.

### Measurement of Area of a Triangle.

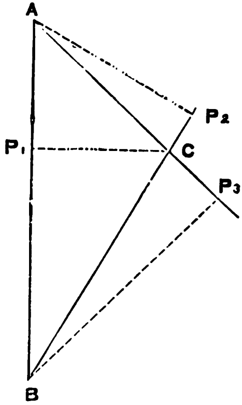


FIG 21.

The figure ABC is a sketch of the triangle on a smaller scale.

1. Choosing AB as base,

$\text{Area} = \frac{1}{2}\,AB \times CP_1$

$AB = 20{\cdot}12$ cm. $CP_1 = 7{\cdot}3$ cm.

$\therefore \text{Area} = \frac{1}{2} \times 20{\cdot}12 \times 7{\cdot}3$

$= \underline{73{\cdot}438 \text{ sq. cm.}}$

2. Choosing BC as base,

$\text{Area} = \frac{1}{2}\,BC \times AP_2$

$BC = 15{\cdot}05$ cm. $AP_2 = 9{\cdot}75$ cm.

$\therefore \text{Area} = \frac{1}{2} \times 15{\cdot}05 \times 9{\cdot}75$

$= \underline{73{\cdot}368 \text{ sq. cm.}}$

3. Choosing AC as base,

$\text{Area} = \frac{1}{2}\,AC \times BP_3$

$AC = 10{\cdot}05$ cm. $BP_3 = 14{\cdot}62$ cm.

$\therefore \text{Area} = \frac{1}{2} \times 10{\cdot}05 \times 14{\cdot}62$

$= \underline{73{\cdot}465 \text{ sq. cm.}}$

**Area of a Polygon.**—The area of any plane rectilinear figure, such as ABCDEFGH, can be found by dividing it into triangles as by the dotted lines, and then finding the areas of all the triangles and adding them together.

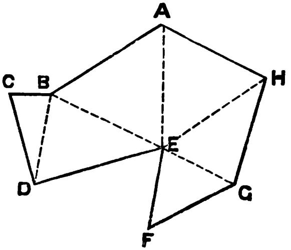


FIG. 22.

**Area of a Curvilinear Figure.**—Similarly, the area of any plane curvilinear figure, such as ABC (Fig. 23), can be found to any required degree of approximation by marking out the sides into short straight lengths and then dividing into triangles as shown, and finding the area of each triangle.

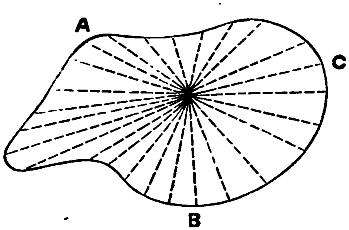


Fig. 23.

Such a process would, however, be very laborious, and we may in practice find the area of such a figure much more readily by the indirect method of cutting it out of a sheet of some uniform material and then weighing it.

Exercise 9.—*To find the area of a certain irregular figure drawn on a piece of card.*

*Instructions.*—The first thing to do is to find how many square cm. of the card weigh a gram. To do this, trim the card so as to make it an exact rectangle or triangle as large as possible. Then find its area. Afterwards weigh it.

Thus you find that . . . . grams of card have an area of . . . . sq. cm., hence 1 gram of card has an area of $\frac{\ldots}{\ldots}$ sq. cm. Now cut out and weigh the figure, and from the weight *calculate its area.*

**Curvilinear Areas that can be calculated.**—The area of certain geometrical figures, such as circles, ellipses, etc., can be calculated.

### TO FIND BY GEOMETRY THE AREA OF A CIRCLE OF KNOWN RADIUS.

Let ABCD (Fig. 24) be the circle, O its centre.

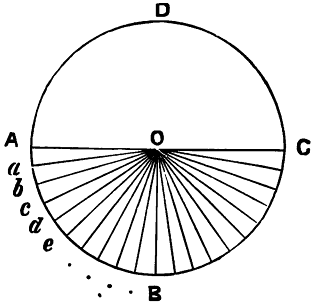


FIG. 24.

Divide it by any diameter AC.

Mark off along the circumference ABC points A, *a*, *b*, *c*, *d*, *e* . . . . at very small equal distances apart, and join each of these points to the centre O.

Now imagine the circle to be cut along each of the radii so drawn and the circumference to be unrolled; we thus obtain Fig. 25.

Now imagine the other semicircle to be treated in the same way. This gives Fig. 26. Now let the two halves be fitted together, for it is evident that they will fit if the bases of the triangles have been made equal. We thus obtain the parallelogram of Fig. 27, which, if the triangles have been made small *enough, is equal* in area to the circle.

Now, when the triangles are small enough, the length of this parallelogram is half the circumference, and its height is the radius.

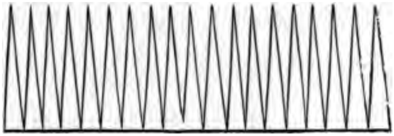


FIG. 25.

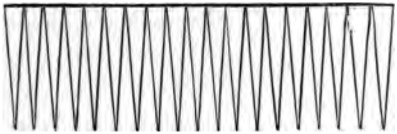


FIG. 26.

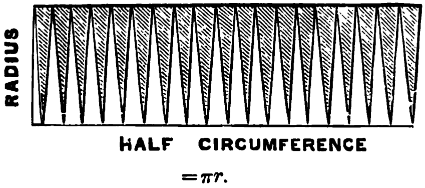


FIG. 27.

$\therefore$ Area of parallelogram = half circumference × radius

$\therefore$ The area of the circle = half circumference × radius,

And since the circumference = diameter × $\pi$

$\therefore$ Half circumference = radius × $\pi$

$\therefore$ Area of circle = radius × $\pi$ × radius

$= \pi r^2$ (where $r$ stands for the radius).

Therefore, *To find the area of a circle* we must *square the radius and multiply the result by* $3\frac{1}{7}$.

EXERCISE 10.—*To verify by experiment the proposition Area of circle of radius* $r = \pi r^2$.

*Instructions.*—Take a piece of cardboard of uniform thickness, and cut it accurately square, say 10 cm. in the side. Describe on it a circle touching the sides at their middle points, A, B, C, D, as in the figure (27*). Join the opposite points, AC and BD. Each of the squares thus formed is the square on the radius. Our proposition states that the area of the circle is equal (very nearly) to $3\frac{1}{7}$ of such squares. Cut out (best in one piece) three of the squares and a seventh part of the fourth, as indicated by the dotted line, and place them in one pan of the balance, and counterpoise. (You do not need to *weigh* them.) Now cut out the circle, and put the pieces composing it back into the balance pan. It will remain exactly counterpoised, showing that the amount of card required to make up the circle is equal to that required to make up three and one-seventh of times the squares on the radius.

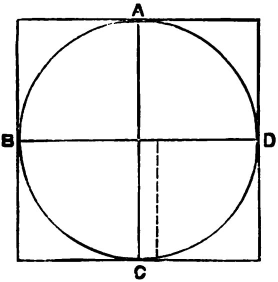


FIG. 27*.

## Numerical Examples on Areas of Circles.

*Ex.* 1. To find the area of a circle whose radius is 10 cm.

$$\begin{aligned} \text{Area} &= \pi r^2 \\ &= 10^2 \times 3\tfrac{1}{7} \\ &= 100 \times 3{\cdot}1428 \\ &= 314{\cdot}28 \text{ square cm.} \end{aligned}$$

*Ex.* 2. To find the area of a circle whose circumference is 20 ft.

$$\begin{aligned} \text{Diameter} &= 20 \text{ ft.} \div 3\tfrac{1}{7} \\ &= 20 \text{ ft.} \times \tfrac{7}{22} = \tfrac{70}{11} \text{ cm.} = 6{\cdot}\dot{3}\dot{6} \text{ cm.} \\ \therefore \text{Radius} &= 3{\cdot}\dot{1}\dot{8} \text{ ft.} \\ \text{But area} &= \text{radius} \times \text{half circumference} \\ &= 3{\cdot}\dot{1}\dot{8} \times 10 \\ &= 31{\cdot}\dot{8}\dot{1} \text{ square feet.} \end{aligned}$$

*Ex.* 3. To find the diameter of a circle whose area is 254·57 square inches.

$$\begin{aligned} \text{Area} &= \pi r^2, \\ \therefore r^2 = \frac{\text{area}}{\pi} = \frac{254{\cdot}57}{3\frac{1}{7}} &= 254{\cdot}57 \times \tfrac{7}{22} \\ &= 127{\cdot}285 \times \tfrac{7}{11} \\ &= \tfrac{890{\cdot}995}{11} \\ &= \tfrac{891}{11} \text{ (very nearly)} \\ &= 81 \quad \text{,,} \qquad \text{,,} \end{aligned}$$

$$\therefore r = \sqrt{81} = 9 \text{ inches,}$$

$$\therefore \text{diameter} = 18 \text{ inches.}$$

**Area of Sphere.**—It can be shown by geometry that the area of the surface of a hemispherical dome, such as that of the figure (Fig. 28), is exactly twice that of the circular base on which it rests. So that *the area of the surface of a complete sphere is four times the area of its central section.*

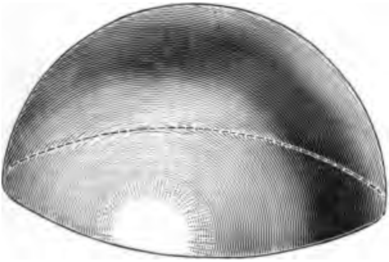


Fig. 28.

**Example.**—How many square feet of gilding will be required to cover a dome which stands on a tower 62·856 feet in circumference?

$$
\begin{aligned}
\text{Diameter of tower} &= 62{\cdot}856 \div 3\tfrac{1}{7} \text{ feet} \\
&= 62{\cdot}856 \times \tfrac{7}{22} \text{ feet} \\
&= \tfrac{439{\cdot}999}{22} \text{ feet} \\
&= \tfrac{440}{22} \text{ feet (very nearly)} \\
&= 20 \text{ feet.} \\
\therefore \text{Radius} &= 10 \text{ feet.} \\
\therefore \text{Area of tower} &= \text{radius} \times \text{half circumference} \\
&= 10 \times 31{\cdot}428 \text{ sq. feet} \\
&= 314{\cdot}28 \text{ sq. feet.} \\
\therefore \text{Area of dome} &= 314{\cdot}28 \text{ sq. feet} \times 2 \\
&= 628{\cdot}56 \text{ sq. feet.}
\end{aligned}
$$

**Area of an Ellipse.**—*Definition.*—An ellipse is a plane figure, such that the sum of the distances of any point on its circumference from two certain points in the interior, called the foci, is always the same.

Thus the figure (Fig. 29) represents an ellipse of which $F_1$ and $F_2$ are the foci, and it will be found that $PF_1 + PF_2$ has the same value wherever P is taken on the circumference.

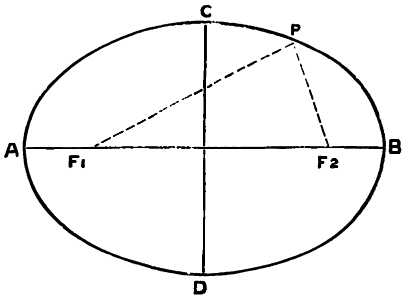


Fig. 29.

*It is evident that we could describe the ellipse by means of a thread $F_1PF_2$* fastened round pins stuck in at $F_1$ and $F_2$ and a finely-pointed pencil placed at P with which to trace out the circumference.

The line AB of Fig. 29 is called the major axis of the ellipse, and the line CD is called the minor axis of the ellipse.

It can be shown by geometry that *the area of an ellipse is* $\pi$ *times the rectangle contained by the semi-axes.*

EXERCISE 11.—*To verify the statement that the area of an ellipse* = $\pi$ *times the rectangle contained by the semi-axes.*

*Instructions.*—Describe an ellipse accurately on a rectangular sheet of uniform cardboard; measure and record the length of major and minor axes. Then find the area of the ellipse by cutting out and weighing exactly as in Exercise 9. Compare the result with the value of $\pi \times$ semi-major axis $\times$ semi-minor axis.

## MEASUREMENT OF VOLUME.

**The Unit of Volume** agreed upon by scientific men is the cubic centimetre, *i.e.* a cube standing on a square centimetre as base. To find the volume of a solid is to find how many such unit cubes it contains.

**Right Prisms.**—It is evident from an inspection of the accompanying figures (30, 31, 32, and 33) that the volume of any one of them may be found in the following manner:—

First find the area of the base; this tells you how many unit cubes will stand on the base, filling up the solid and forming a layer 1 cm. high. Now measure the height of the solid; doing this tells you the number of such layers that will be required to reach to the top. So that *the total number of unit cubes in the solid is obtained by multiplying the number of units of area in the base by the number of units of length in the height;*

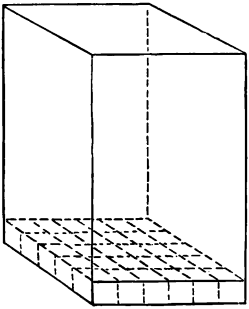


FIG. 30.

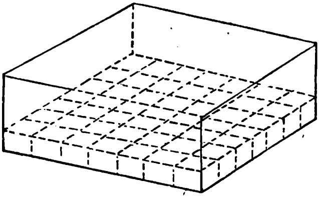


FIG. 31.

*Or, more briefly,* but less correctly expressed—

*To find the volume of such a solid as those represented, multiply the area of the base by the height.*

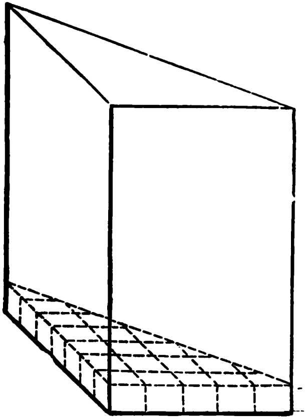


FIG. 32.

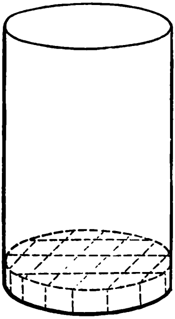


FIG. 33.

It is evident that this rule applies not only to solids which, like those of Figs. 30 to 33, stand upright on their bases, but also to such a solid as that of Fig. 34, where the height is AB measured perpendicular to the base. For if we could cut down the plane CDEF, we should obtain two parts which would fit together into the form of Fig. 30.

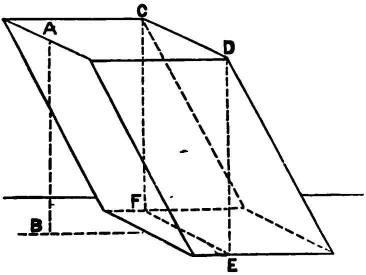


FIG. 34.

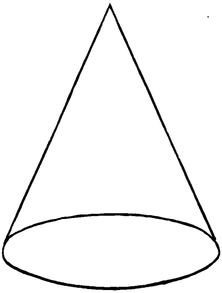


FIG. 35.

The former figures are called *right prisms.* Thus Figs. 30 and 31 are right prisms on rectangular bases, Fig. 32 a right prism on a triangular base, and the cylinder of Fig. 33 may be called a right prism on a circular base. Fig. 34 is called an oblique prism. It is evident, however, that the rule does not apply to such a solid as the cone of Fig. 35, where each layer is of less area than the one below it.

**Litre.**—It follows from what has been said that a cubic decimetre must contain 1000 cubic centimetres, for it will take a hundred to cover the base, forming a layer 1 cm. high, and there will be ten such layers. Similarly, there will be 1000 cubic decimetres in a cubic metre.

A cubic decimetre is called a litre, and is rather less than an English quart, being indeed 1·76 pints (or 61·03 cubic inches). This measure is used on the Continent of Europe as a measure of capacity for wine, and liquids generally.

Since a cubic centimetre of cold water weighs 1 gram, it follows that a litre of cold water weighs 1000 times as much, or 1 kilogram.

EXERCISE 12.—*Measure the height and diameter, and thence calculate the volume of the cylinders given you.*

*Instructions.*—Since it is possible that the cylinders may not be trimmed off quite squarely, you should not be content with less than two or three measures of the height, taken in different places. Let the record be modelled on the following *example :—*

### EXERCISE 12.

**Measurement of Volume of Cylinder.**

**No. 1. Brass cylinder.**

**Diameter 2·6 cm. Height 4·8 cm.**

**4·75 cm.**

**4·75 cm.**

**Average height = 4·766 cm.**

**Rad. = 1·3 cm. $\therefore r^2 = 1{\cdot}69$.**

**$\therefore$ Area of base $= \pi r^2 = 1{\cdot}69 \times 3\frac{1}{7} = 5{\cdot}311$ sq. cm.**

**$\therefore$ Vol. = area of base × height = 5·311 × 4·766 cub. cm.**

**= 25·31 cub. cm.**

EXERCISE 13.—*Find the volume of the triangular prism of wood given you.*

*Instructions.*—Record with a figure as in the following example:—

### EXERCISE 13.

**Measurement of Volume of Triangular Prism of Wood.**

**The prism was shaped as shown in the sketch.**

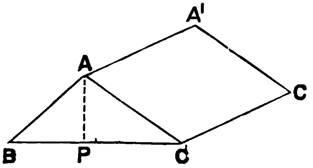


FIG. 36.

**Area of triangle ABC $= \frac{1}{2} \times$ BC × AP**

**BC = 8·2 cm. AP = 3·15 cm.**

**$\therefore$ Area of triangular base $= \dfrac{8{\cdot}2 \times 3{\cdot}15}{2} = 12{\cdot}91$ sq. cm.**

**Height of prism = AA′ = 6·32 cm.**

**$\therefore$ Vol. of prism = area of base × height**

**= 12·91 × 6·32 cub. cm.**

**= *81·59* cub. cm.**

EXERCISE 14.—*Verify for yourself the accuracy of your weights.*

*Instructions.*—Take a vessel whose cubical contents you can find accurately by measurement. Then, having found the capacity in cubic cm. by measurement and calculation, counterpoise the empty vessel in one pan of the balance, fill with water, and weigh the water contained; if your weights are correct, they will show the number of cubic cm. in the vessel to be the same as the number of grams of cold water that it will hold.

It is best to take an accurately made cylindrical vessel for this experiment. The tin vessel with which you are provided does very well. Its diameter should be measured first at the top in several places, and then at the bottom in several places, and the mean value taken. The height must be measured *inside* in several places, and the mean taken.

In filling with water, great care must be taken to fill the vessel exactly to the brim. The final adjustment of level should be made after the vessel has been placed in the balance pan, by means of a glass tube (called a pipette), by which small quantities of water can be added or removed as required.

**To find the Volume of an Irregular Solid by Displacement of Water.**—It would be difficult and in many cases impossible to find accurately by measurement the volume of a very irregular solid, such, for instance, as a fragment of stone or glass. The volume in such a case may however be found with great accuracy in the manner described in the following experiment:—

EXERCISE 15.—*Find by displacement of water the volume of a pebble.*

*Instructions.*—Take a test tube, just wide enough for the pebble to go in; make on the outside a mark with a file; fill with water up to the mark. Place the test tube, so filled, in one pan of the balance, supporting it upright by letting it stand in an empty beaker; now place the pebble by its side in the pan, and then counterpoise the whole with shot (and paper).

Now drop the stone (very gently, of course) into the test tube. It sinks to the bottom, and causes the water to rise above the mark, and the water which rises above the mark is obviously exactly equal in volume to the pebble that has been dropped in. If you put the test tube back in the pan just as it is, the whole would still be exactly counterpoised, since no matter has been removed, and we have only changed the situation of the stone in the pan. But if before putting back the test tube you take away the water that has risen above the mark (by means of a pipette), you will have removed exactly as much water as is equal in volume to the stone, and the counterpoise will now be too heavy. Now add weights to the pan till equilibrium is restored. The weights added give you the weight of the water displaced by the stone. But each gram of water occupies a cubic cm., therefore the number of grams of water that are gone is the same as the number of cubic cm. occupied by the stone, that is, the volume of the stone.

In doing the experiment certain precautions are necessary to secure an accurate result.

*Great care must be taken* to adjust the liquid exactly to the same level each time. It will be observed that the surface of the liquid is not plane, but curved, in what is called a *meniscus* (or crescent-like shape), the curvature depending on the width of the test tube.

It is the *lowest point of this curve* that can be most precisely observed, and it is this that should be adjusted to the level of the mark on the glass. The mark on the glass must be held at the level of the eye in adjusting the liquid; to be sure that it is at the right level, use a mark on the wall or window at the level of your eye as you stand upright, and then hold the test tube so that the file mark comes between your eye and the spot on the wall.

To secure that the test tube is vertical when you make the adjustment, hold it by the rim, and let it swing freely between the fingers. The sides of the test tube above the water should be wiped dry with a handkerchief or blotting-paper before putting it into the balance pan.

*N.B.*—Keep the stone used in this experiment, as it will be wanted again.

**Advantage of using a narrow vessel.**—You have been directed in the last experiment to use a vessel only just wide enough to admit the object whose volume it is required to find. In order to understand the advantage of using a narrow vessel, it is necessary to remember that however much care you may take in the adjustment of the level to the mark, you cannot be sure of not making a small error. But the same error of adjustment will make a much greater error in the weight of liquid removed when the vessel is wide than when it is narrow. See the figures (A and B) on opposite page in illustration of this.

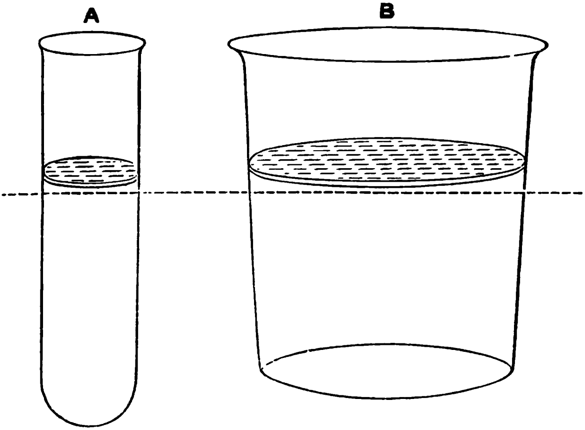


Fig. 37.—The quantity of water above the mark in A is much less than in B, though the error of adjustment is the same.

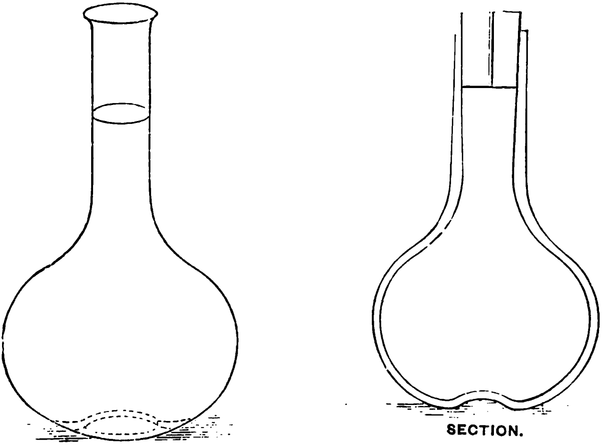


Fig. 38.

Fig. 39.

*Specific*-Gravity Flasks

EXPERIMENT 1.—*To compare the densities of two liquids which do not mix by the method of balancing columns in a* U*-tube.*

*Instructions.*—The U-tube should be made of a glass tube 8 or 10 mm. in internal diameter. The arms should be at least 30 cm. long and as near together as possible. The tube should be held vertically resting on the table. The heavier liquid should be poured in first, and the other poured gently on to this through a funnel, care being taken not to drive the heavier liquid past the bend. The result will be most accurate when the balancing columns are as long as possible, since an error in the measurement of the height will then be but a small fraction of the whole. For this reason the column of the lighter liquid should reach from nearly the top of the tube to nearly the bottom. See Fig. 42.

The record should contain a lettered diagram, and the measures should all be taken from the level of the table. Thus—

Height of A above table = . . . . cm.
" C " = . . . . cm.
∴ AC = cm.

Height of B above table = . . . . cm.
" C " = . . . . cm.
∴ BC = cm.

$$\therefore \frac{\text{Density of liquid (A)}}{\text{Density of liquid (B)}} = \frac{BC}{AC} = \ldots\ldots$$

Compare in this way:—

*The density of mercury with that of water.*
" " *turpentine* " "
" " " " *mercury.*

5. Place the vessel filled to the mark, with the sinker inside, in one pan of the balance; put the block by its side, and counterpoise.

6. Now take out the sinker, put in the block, and replace the sinker on the top to keep it down, taking care that it cannot fall off and break through the bottom of the vessel, and remove the water that rises above the mark.

*N.B.*—In doing this it is best to empty out the original water, to put in the block, and then the sinker on the top, and then to fill up with water to the mark.

7. Now add weights to restore equilibrium. The weights thus added tell you the weight in grams, and therefore the number of cubic cm. of water displaced by the wooden block. You may verify the result by finding the volume of the same block by measuring it.

**On the Volume of a Sphere.**—It can be shown by geometry that the volume of a sphere is $\frac{2}{3}$ *of the volume of the circumscribing cylinder*, *i.e.* of a cylindrical box into which the sphere would exactly fit, as in Fig. 40.

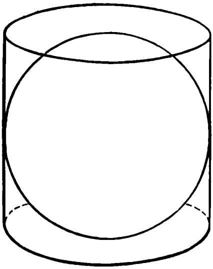


Fig. 40.—Sphere and circumscribing Cylinder.

Exercise 18.—*To verify this statement.*

*Instructions.*—Take your wooden sphere, and first find its volume by displacement as in the last experiment, then measure the diameter with great care (see p. 24). This gives you the diameter of the circumscribing cylinder, and also its height, from which you can calculate the volume. Take $\frac{2}{3}$ of this *volume, and you will* find, if your experiment has been well done, that you obtain very nearly the value that you have just found for the volume of the sphere. If the ball were a true sphere, which it is probably not, and if your measuring, adjusting of level, and weighing could be made with perfect accuracy, you would obtain absolutely concordant results.

EXPERIMENT 19.—*Second Experiment on volume of a sphere.*

*Instructions.*—The same result may be exhibited in another way. It is easy to turn on the lathe a cylinder of the same radius as the sphere, and by wrapping thin writing-paper round the end of the cylinder, to make a cylindrical box of the same size, which is closed below by the cylinder: the depth of this box can also be very accurately adjusted to the diameter of the sphere by pushing in or pulling out the wooden base, and when it is once adjusted, the whole can be securely tied up and rendered impervious to water by dipping it into melted paraffin wax. The box, which is represented in the accompanying figure (41), can now be placed in the balance pan and counterpoised, and then filled with water, and the water weighed. If now the box be removed from the pan, and the sphere immersed in it and then withdrawn, it will be found on restoring it to the balance pan that just $\frac{2}{3}$ of the water has overflowed. Indeed, if the walls of the vessel are not made of too many *folds of paper,* they will be sufficiently transparent, when the

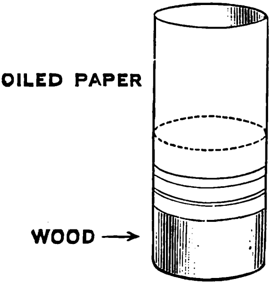


FIG. 41.—Method of realising the circumscribing Cylinder.

vessel is held up to the light, to allow it to be seen that the liquid now only fills the vessel to $\frac{1}{3}$ of its depth.

*N.B.*—The sphere should be slightly oiled, to prevent any water adhering to it when it is withdrawn. It may be withdrawn by sticking a pin into it.

**Measurement of the Volume of Solids that are Dissolved or Chemically Acted on by Water.**—It often happens that a solid is dissolved by water, as for example a piece of rock-salt, or that it is otherwise acted on, as for instance a piece of sodium. In such cases it may sometimes be protected from the action of the water by being coated with a thin varnish, which does not appreciably alter its bulk. But it is generally advisable to find some other liquid in which to submerge it. For instance, a piece of rock-salt or of copper sulphate may be immersed in a saturated solution of the same substance, *i.e.* in water which has already dissolved as much of the substance as it is able, or some other liquid, such as turpentine, which does not dissolve the substance, might be made use of. But it has to be remembered that with any other liquid except water a gram of the liquid will not occupy a cubic cm., and if we are to use another liquid we must first find how many cubic cm. of it go to a gram.

EXPERIMENT 20.—*To find the volume of a crystal of copper sulphate of known weight.*

*Instructions.*—First weigh the crystal; then take a saturated solution of copper sulphate, and find how many cubic cm. of it go to a gram.

*To do this, counterpoise* an empty specific-gravity flask, then fill with water, and weigh the water contained; this tells you the number of cubic cm. in the flask.

Now fill the (counterpoised) flask with the saturated solution, and weigh it. From this you find that so many grams of the solution occupy so many cubic cm., from which you can deduce how many cubic cm. 1 gram occupies.

Now proceed to find, by means of a test tube with a mark, the weight of solution displaced by the crystal. You will find that it is so many grams, and knowing how many cubic cm. each gram occupies, you can find at once the volume of the solution displaced by the crystal, and therefore of the crystal.

**The volume of a piece of wood which floats in water** might evidently be found by displacement of spirits of wine, or some other light liquid in which it would sink.

EXPERIMENT 21.—*Find by displacement of spirits of wine the volume of the sphere used in Exercise* 18.

## RELATIVE DENSITY, OR SPECIFIC GRAVITY.

**Definition.**—The *relative density* or *specific gravity* of a substance is the number which expresses the ratio of its weight to the weight of an equal volume of water; in other words—

Relative density of a substance

$$= \frac{\text{weight of substance}}{\text{weight of equal volume of water}}.$$

Thus a piece of platinum weighs 21·5 times as much as an equal volume of water, and its relative density therefore is 21·5, while a certain quantity of alcohol only weighs $\frac{8}{10}$ as much as an equal volume of water, and its relative density is therefore $\frac{8}{10}$ or ·8.

The relative density of water is obviously 1; and since a cubic cm. of water weighs 1 gram, it follows that a cubic cm. of platinum weighs 21·5 grams, and a cubic cm. of alcohol ·8 grams, so that the relative density of a substance is expressed by the same number as the weight in grams of a cubic cm. of it.

To find the relative density of a substance of which a body is made, we have only to find its weight and volume, for its volume in cubic cm. tells us what it would weigh in grams if it were made of water, so that we then know the value both of numerator and denominator in the fraction

$$\frac{\text{weight of object}}{\text{weight of equal volume of water}}.$$

But the area of the circular cross-section $=\pi r^2$, where $r$ is the

$$\therefore \pi r^2 = \cdot 008 \text{ sq. cm.}$$

$$\therefore r^2 = \frac{\cdot 008}{\pi} \text{ sq. cm.}$$

$$= \cdot 008 \times \tfrac{7}{22} = \cdot 002545 \text{ sq. cm.}$$

$$\therefore r = \sqrt{\cdot 002545} \text{ cm.}$$

$$= \cdot 05044 \text{ cm.}$$

$\therefore$ thickness of wire $= 2r = \cdot 10088$ cm.

# PART II.

# HYDROSTATICS.

(15 *Experiments.*)

will be released from the friction, and will come to rest in its true position. The level at which the water-line cuts the pencil can then be noted by looking *underneath* the surface. The following example of the record of an experiment made in this way will explain the arguments used.

### *Example of an Experiment to find the Density of a Pencil by Flotation.*

The pencil was 17 cm. long, and floated as in the figure (Fig. 48), with 10·5 cm. below the surface.

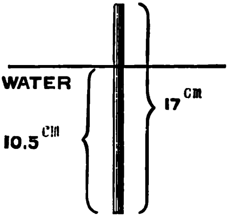


FIG. 48.

∴ Weight of rod of wood 17 cm. long =weight of *similar* rod of water 10·5 cm. long

∴ The pencil is lighter than water in the ratio of 10·5 to 17

∴ Density of pencil=

$$\text{density of water} \times \frac{10{\cdot}5}{17}$$

$$= 1 \times \frac{10{\cdot}5}{17}$$

$$= \frac{10{\cdot}5}{17} = {\cdot}617.$$

EXPERIMENT 12.—*To find by flotation the density of a rectangular block of wood.*

*Instructions.*—The block must be floated in water, as in the figure (Fig. 49), and the depth of immersion noticed. The argument will be precisely the same as in the last experiment,

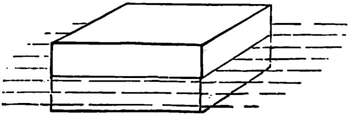


FIG. 49.

since the block differs in fact from the pencil only in being shorter and thicker. Certain precautions are however necessary. (1) The block may not float with its upper surface quite horizontal, so that the depth of immersion may be different at different corners. Measure, therefore, the depth at each corner, and take the mean. (2) To observe the depth accurately, pencil-marks should be made on the block near each corner, and the position of the water-line among these marks noticed by holding the eye just below the level of the surface. (3) The water will cling by adhesion to the block all round the edge, and the weight of the water thus raised above the surface (see Fig. 50) will drag down the block. This clinging may be prevented by oiling the block beforehand.

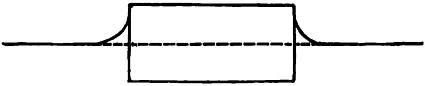


Fig. 50.

**Experiment 13.**—*To find by flotation the density of a right triangular prism of wood.*

*Instructions.*—Oil the prism before floating it. Suppose that it floats as in the diagram (Fig 51).

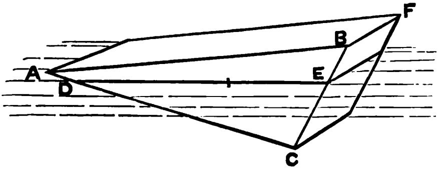


Fig. 51.

$$\text{Volume of whole piece of wood} = \text{area ABC} \times \text{BF}$$
$$\text{and vol. of submerged part} = \text{area DEC} \times \text{BF}$$

∴ Weight of water whose vol. is DEC × BF = weight of wood whose vol. is ABC × BF

∴ The wood is lighter than water in the ratio $\frac{\text{DEC} \times \text{BF}}{\text{ABC} \times \text{BF}}$, *i.e.* in the ratio $\frac{\text{DEC}}{\text{ABC}}$

∴ Density of the wood = density of water × $\frac{\text{DEC}}{\text{ABC}}$

$$= 1 \times \frac{\text{DEC}}{\text{ABC}} = \frac{\text{DEC}}{\text{ABC}} = \frac{\cdot\ \cdot\ \cdot}{\cdot\ \cdot\ \cdot}$$

EXPERIMENT 14.—*To find the density of* (1) *a saturated solution of common salt,* (2) *methylated spirits of wine, by floating a pencil first in water, and then in the liquid in question, and observing the depth of submersion in each.*

*Instructions.*—Argue as in the following example:—

The pencil is found to float in water with ($m$) cm. submerged
„ „ „ the solution with ($n$) cm. submerged
∴ Weight of a rod of water ($m$) cm. long = weight of pencil,
And „ „ solution ($n$) cm. long = „ „

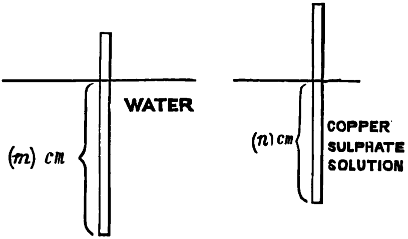


FIG. 52

$\therefore$ The weight of a rod of water (*m*) cm. long = weight of a similar rod of the solution (*n*) cm. long

$\therefore$ The solution is denser than water in the ratio of (*m*) to (*n*)

$\therefore$ Density of solution $= \frac{(m)}{(n)}$.

*N.B.*—Instead of a pencil, which is troublesome to hold upright, you may use a glass tube stopped at the bottom with wax and weighted with shot or mercury. The depth of immersion may be noted on a paper scale placed inside the tube.

EXPERIMENT 15.—*Make a Cartesian diver by blowing a bulb on the end of a narrow glass tube.*

*Instructions.*—Cut off the neck 4 or 5 cm. below the bulb. Weight it by wrapping copper wire round the stem till it just floats, as in the figure (Fig. 53), with as little as possible of its volume above the water. Now place it in a tall jar filled nearly full, as in Fig. 54, with a piece of india-rubber

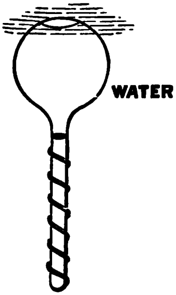


FIG. 53.

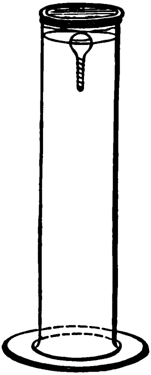


FIG. 54.

tied air-tight over the mouth. On pressing the india-rubber, the water will be seen to rise inside the diver, and the diver will descend to the bottom. Explain why. If the diver be very accurately adjusted, it will not rise again after reaching the bottom. Explain why not. Try the same experiment with jar only half full of water, and then explain the object of filling it nearly full.

*N.B.*—In thinking of the explanation, regard the diver as an object made of glass, wire, and air, whose volume we can alter while its weight remains always the same.

# PART III.

# BAROMETER AND BOYLE'S LAW.

(3 *Experiments.*)

## PART III.

# BAROMETER AND BOYLE'S LAW.

EXPERIMENT 1.—*To make a barometer.*

*Instructions.*—Fill the barometer tube with mercury cautiously, by means of a small funnel, till within about 2 cm. from the top; then close the end with the finger, and invert the tube twice or thrice, so as to let a large bubble of air travel up and down the tube and sweep up the smaller bubbles. When these are got rid of, fill up to the top, close the end with the finger, and invert the tube in a small mortar of mercury standing in a tray; remove the finger, and the mercury in the tube will descend to a certain height above the level of that outside. Measure this height. Incline the tube till the mercury nearly reaches the end, and again measure the *height* of the upper surface of the mercury above the lower. If you have succeeded in getting rid of all air-bubbles, you will find the height unaltered.

To test the absence of air, incline the tube rapidly, so as to let the mercury strike the end sharply; if there is no air, the liquid *will strike the end* with a metallic click.

## EXPERIMENTS TO VERIFY BOYLE'S LAW.

**Preliminary Remarks.**—Gases, like liquids, transmit in all directions the pressure applied to their surface, but they differ from liquids in being much more compressible.

Suppose B to be a hollow cylinder, into which a weightless piston A fits perfectly air-tight, yet without friction. If B be full of a liquid, and we press upon the top of A, this pressure is transmitted equally on all equal surfaces in all directions through the liquid, but the liquid does not become appreciably smaller in volume, unless the pressure is enormously great. If, on the other hand, the cylinder be filled with a gas instead of a liquid, it will become very appreciably smaller the more we press on the piston. It was discovered by Robert Boyle (born 1626, died 1691) that the volume of any permanent gas diminishes exactly in proportion as the pressure on it is increased, and that, conversely, if we diminish the pressure, the gas expands in the same proportion. This is known as "Boyle's Law." We see from it that if the pressure, represented by the arrow on the top of the piston, be doubled, the volume of the gas will be halved. If the pressure be diminished to one-third, the gas will expand till its volume becomes thrice *as great,* and so on.

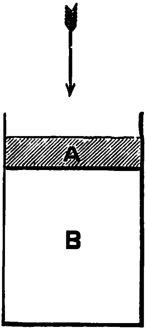


Fig. 55.

EXPERIMENT 2.—*To verify Boyle's Law.*

*Instructions.*—It would be impossible to make an air-tight piston, like that in the figure (Fig. 55), which would work without friction, but by using a bent tube, like that in Fig. 56, and pouring in a little mercury so as to close the bend, we entrap some air in the short arm, and at the same time make a mercury piston which can be pushed further up by pouring more mercury down the long leg. To prove the truth of Boyle's Law, we must observe the volume of the air to start with, and the pressure on it; then we must several times increase the pressure to a known extent by pouring in more mercury, and observe whether the volume is in each case diminished in the same proportion. The volume of the air may be represented as so many cm. of the tube, viz. the distance between C and $B_1$.

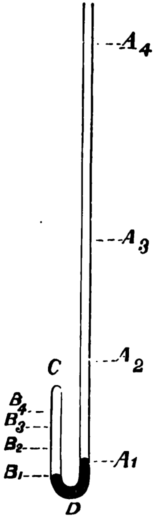


FIG. 56.

*N.B.*—Since the tube narrows a little where it is sealed, allowance must be made for this, which may be done by reckoning the top of the inside of the tube to be a little lower than it really is. It is best not to try to measure directly the distance from C to $B_1$, but to measure first the height of C above the table D, and then the height of $B_1$, and to subtract the latter. In this way we find the volume, to start with ($V_1$).

If the mercury at $A_1$ is at the same level as at $B_1$, then the pressure on the gas is that of the atmosphere pressing on the mercury at $A_1$. If $A_1$ *is at a* higher level than $B_1$ (as in the figure), then the pressure due to the head of mercury above $B_1$ must be added to that of the atmosphere. If, on the other hand, $B_1$ is higher than $A_1$, the pressure due to the head of mercury must be subtracted from that of the atmosphere. Accordingly the pressure ($P_1$) to begin with is equal to the atmospheric pressure (H), which is found by observing the height of the barometer at the time of the experiment, *plus* ($A_1D-B_1D$).

Thus we have $P_1=H+A_1D-B_1D$, while $V_1=CD-B_1D$.

Now let more mercury be poured into the long leg by means of a little funnel, so that $B_1$ rises to some such position as $B_2$, and $A_1$ to $A_2$.

The volume of the imprisoned air is now $V_2=CD-B_2D$, and the pressure on it is $P_2=H+A_2D-B_2D$.

Now add mercury a third and a fourth time (the last time completely filling the long leg, which should be at least 1½ metres long), and find the volumes $V_3$ and $V_4$ of the imprisoned air and the corresponding pressures $P_3$ and $P_4$.

Now if the volume has decreased exactly in proportion as the pressure has been increased, that is, if Boyle's Law is true, then the product Volume × Pressure must always retain the same value, for in proportion as one factor diminishes, the other increases. To test this, arrange your results as in the following table:—

| V | P | V × P |
|---|---|---|
| $V_1=$ . . . | $P_1=$ . . . | $V_1 \times P_1=$ . . . |
| $V_2=$ . . . | $P_2=$ . . . | $V_2 \times P_2=$ . . . |
| $V_3=$ . . . | $P_3=$ . . . | $V_3 \times P_3=$ . . . |
| $V_4=$ . . . | $P_4=$ . . . | $V_4 \times P_4=$ . . . |

The agreement of the products in the last column proves the truth of the law so far as air is concerned, and between the pressures at which you begin and end the experiment.

*N.B.*—If the tube of which the manometer is made is not of uniform bore at the closed end, but, for example, tapers towards the end, then the volume of the air as it is compressed will appear larger than it really is, since it will take up a greater length of a narrower tube. Hence care must be taken to select a uniform tube for making the manometer. With a carefully chosen tube the results of the last column should not differ from each other by more than two or three parts in a thousand.

EXPERIMENT 3.—*To test Boyle's Law for lower pressures.*

*Instructions.*—In the last experiment we started with our imprisoned air at the atmospheric pressure, and then increased the pressure by pushing in the mercury piston by means of more mercury. We will now make an experiment which is equivalent to diminishing the pressure on the piston, and letting the air expand. Fill a barometer tube to within about 10 cm. of the top, as in Fig. 57. By placing the finger over the mouth of the tube we imprison a certain volume ($V_1$) of air, which is of course at the pressure of the atmosphere. Now invert the tube, as in Fig. 58. The air rises to the top,

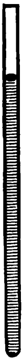


FIG. 57.

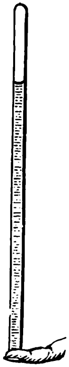


FIG. 58.

where, if the tube is of the same width throughout, it occupies the same length of the tube as in Fig. 57. Since, however, the tube may not be uniform, it is best to measure the length occupied by the air at the *upper* end, keeping the mouth closed by the finger, and to call this ($V_1$).

Now if we open the tube under mercury, the mercury in the tube will fall, for the pressure of the air outside cannot balance the pressure of the imprisoned air as well as a long column of mercury. Accordingly the imprisoned air will expand, and the mercury will fall; but the more the air expands, the less does it press on the mercury column, so that a point is soon reached, as in Fig. 59, at which the pressure of the expanded air and the weight of the column of mercury is equal to the atmospheric pressure. The volume ($V_2$) of the imprisoned air is now AM, which we can measure (always making allowance for the narrowing of the tube at the top). The pressure ($P_2$) on it is that of the atmosphere *minus* the pressure due to the column of mercury LM, which the atmospheric pressure has to balance in addition to that of the imprisoned air

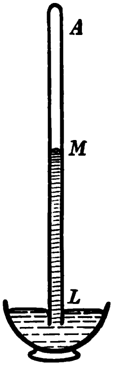


FIG. 59.

As in the last experiment, we expect to get

$$V_1 \times P_1 = V_2 \times P_2.$$

We cannot get the same quantity of air to expand further, so that the experiment is now at an end.

But we may with advantage repeat it with a different quantity of imprisoned air to start with, for the sake of showing that in each experiment the two products always agree.

# PART IV.

# MECHANICS.

(39 *Experiments.*)

## (1) LEVERS AND PARALLELOGRAM OF FORCES

(11 *Experiments.*)

# PART IV.

# MECHANICS.

## (1) LEVERS AND PARALLELOGRAM OF FORCES

EXPERIMENT 1.—*To prove that the turning power (or moment) of a force is proportional to the distance of its direction from the axis.*

*Instructions.*—To do this we must show that, on doubling the distance from the axis, the turning power is doubled, and so on.

Pour shot into a pill-box till it weighs between 50 and 100 grams. Make two other pill-boxes of equal weight. Use your metre measure as a lever, balancing it on the edge of a triangular file as a fulcrum, below its centre of gravity. (*N.B.*—The centre of gravity may not be exactly in the middle, and its position must be found by the preliminary experiment of observing where the lever balances.)

At 15 cm. from the fulcrum place your 100-gram weight on its edge, as in the figure (Fig. 60).

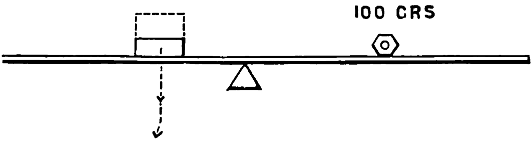


*FIG.* 60.

On the other side place one of the pill-boxes, sliding it about till the lever balances.

The 100-gram weight at 15 cm. from the axis exerts on the lever a turning power equal and opposite to that exerted by the pill-box. Now move the 100-gram weight to a distance of 30 cm. You will find that it will now balance the second pill-box placed on top of the first, *i.e.* its turning power, or moment, is doubled. Similarly, you will find that, if placed at a distance of 45 cm. from the fulcrum, it will balance the three pill-boxes.

From this experiment we see that we obtain the measure of the moment or turning power of a force by multiplying the value of the force by the distance of its direction from the axis.

EXPERIMENT 2.—*To show that when several forces act on a lever their turning power is to be measured by the sum of their moments taken separately.*

*Instructions.*—Balance the lever at its centre of gravity as before. Place, on the right-hand side, known weights, at different distances from the fulcrum. Measure these distances carefully, and multiply the amount of each weight by its distance, so as to obtain its moment. Now, on the other side of the fulcrum place a single weight, at such a distance that it balances the rest. You will now find that the moment of the force on the left side is equal to the sum of the moments of the forces on the right side.

**Principle of Moments.**—This experiment and those which follow may be regarded as illustrations of the principle that *when a body acted on by different forces is at rest, the sum of the moments of the forces tending to turn it one* *way round is equal to the sum of the moments of the forces tending to turn it the opposite way round.*

EXPERIMENT 3.—*To find the weight of an object without using an ordinary balance, by the principle of moments.*

*Instructions.*—As an object take one of the weighted pill-boxes. Balance the lever as before, and place the pill-box at some distance, say 45 cm., from the fulcrum. On the other side place a 100-gram weight, and move it about till you find where it balances. Observe its distance from the fulcrum, and thus find its moment. Then, if X=the weight of the pill-box, you have—

Moment of weight of pill-box=moment of 100-gram weight,

or, $X \times 45 =$ moment of 100-gram weight,

from which you can find X.

Verify your result by weighing the pill-box in a balance.

**On the Balance.**—The beam of a balance is evidently a lever, of which the two arms are equal in length. When we balance an object placed in one pan by putting weights in the other, we make the moments on each side of the fulcrum the same, and argue that the weights at the two sides must be the same, because, acting on arms of equal length, they produce equal moments. In practice it is, however, very difficult to make the two arms of the balance exactly of equal length; indeed, with a very delicate balance, a sunbeam falling on one side of the beam will cause that side to expand and lengthen, and will thus interfere with the accuracy of the weighing. Delicate weighings are therefore made by what is *called the method* of "taring"—a name derived from the French word *tare*, a counterpoise. The method is as follows:—

**Instructions for Weighing by Taring.**—Place the object to be weighed in the right-hand pan, and counterpoise it with shot and tinfoil (or paper) placed in the left-hand pan. Now remove the object, and substitute weights which again balance the counterpoise. It is evident that these weights must be equal to the weight of the object, since, acting on the *same* arm, they produce the same moment. Thus, however much longer one arm of the balance may be than the other, the method of taring enables us to weigh correctly with it.

It is interesting to test the accuracy with which the arms of your balance have been adjusted to the same length. To do this, proceed as follows.

EXPERIMENT 4.—*To find the ratio between the lengths of the arms of the balance.*

*Instructions.*—First adjust the balance for weighing in the usual manner, by adding, if necessary, shot and paper to the lighter pan till it balances the other with the beam horizontal.

Now place in the left-hand pan a 50-gram weight, and counterpoise it with shot and paper in a watch-glass placed in the right-hand pan. Call this watch-glass No. 1. Remove the 50-gram weight, and counterpoise with another watch-glass containing shot and paper, in place of the 50-gram weight. Call this watch-glass No. 2. It is clear that, even if the arms of the balance be of unequal length, the weight of watch-glass No. 2 is exactly equal to 50 grams, since each serves to balance watch-glass No. 1.

*Now remove* watch-glass No. 1 altogether, and place the

50-gram weight in one pan, and watch-glass No. 2, which also weighs 50 grams, in the other, and observe whether the balance is still in equilibrium. If not, the arm which is raised must be the shorter. Add known weights (P) to that side till equilibrium is restored. Then

50 grams in one pan balance 50+P grams in the other; therefore the one arm is longer than the other in the ratio of $\frac{50+P}{50}$; and the weights which you use in weighing any object will be greater or smaller than the true weight of the object (according as the object hangs from the long or the short arm) in the proportion $\frac{50+P}{50}$.

You will probably find that your balance is so accurate that the error introduced in this way is never as much as $\frac{1}{1000}$ of the whole weight.

EXPERIMENT 5.—*To find the weight of the lever without using a balance, by the principle of moments.*

*Instructions.*—First find, by balancing, the position of the centre of gravity of the lever. Then support it on the edge of the file as fulcrum, with the centre of gravity say 10 cm. from the fulcrum. Now, on the opposite side of the fulcrum, place a 50-gram or other sufficient weight at such distance that it balances the lever.

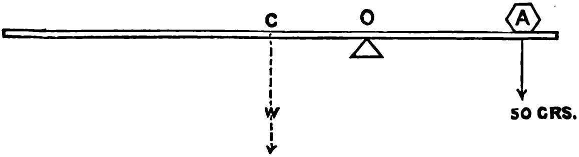


FIG. 61.

Then it is evident on referring to the diagram (Fig. 61) that, if W be the weight of the lever,

$$W \times OC = 50 \text{ grams} \times OA$$

$$\therefore W = 50 \text{ grams} \times \frac{OA}{OC}.$$

EXPERIMENT 6.—*A lever is balanced horizontally, but not at its centre of gravity. It carries various weights at both sides of the fulcrum. Count up the moments of the forces acting on one side of the fulcrum, and show that their sum is equal to the sum of the forces acting on the other side.*

EXPERIMENT 7.—*To illustrate the case of common occurrence, in which two men carry on their shoulders the ends of a beam, from which is slung a weight, but not midway between them; and the question arises, What share of the weight is borne by each?*

*Instructions.*—Support a lever (your half-metre measure) near one end B, on a fulcrum, and near the other end A, by hanging it from one pan of a balance, as shown in the figure (Fig. 62), and place a counterpoise in the other pan D, so that the lever is balanced horizontally. Let the points of support A and B be for convenience 40 cm. apart. Now place on the lever a weight of 100 grams first midway between A and B.

You will find that to balance the lever you must now place a weight of 50 grams in the pan D, showing that the weight of 100 grams is shared equally between the supports at A and B.

Now move the 100-gram weight to a point C, nearer to A, say 15 cm. from A and 25 from B, and find what weight (W) it is necessary to put in the pan D in order that the lever may balance.

It is evident that the moment of the force W tending to turn the lever one way round must be equal to the moment of the 100 grams tending to turn it the opposite way round;

$$\text{or, } W \times 40 = 100 \text{ grams} \times 25$$

$$\therefore W = 100 \text{ grams} \times \frac{25}{40},$$

*i.e.* $\frac{25}{40}$ of the weight is now borne by the support A,

and the remaining $\frac{15}{40}$ " " " B.

Your experiment should confirm this result.

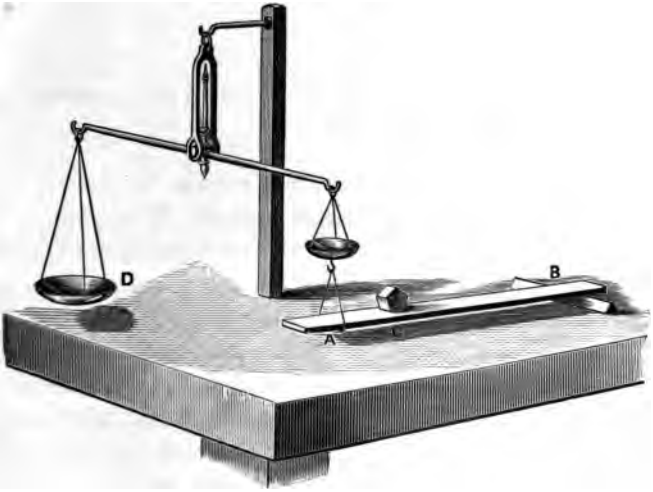


Fig 62

Now move the 100-gram weight into another position, say near to B, and show that now the share of the weight borne by the support A is less than the share borne by B, in *proportion as the distance* from A to the weight is greater *than the distance of B.*

**Resultant.**—In this, and indeed in every case in which a body is at rest under the influence of several forces, any one of the forces is equal and opposite to the *resultant* of the rest.

For example, two parallel forces at A and B acting upwards are balanced by a force of 100 grams at C acting downwards, *i.e.* their resultant is equal to their sum, and acts upwards through the point C, which divides the distance between them proportionally to the forces.

Or again, the resultant of the opposite parallel forces at A and C is their difference which acts at B, a point whose distance from the direction of either force is inversely proportional to the force.

EXPERIMENT 8.—*Experiment in which the forces do not act at right angles to the lever.*

*Instructions.*—Arrange an experiment as in the diagram (Fig. 63), in which the half-metre measure AB, the position of whose centre of gravity (G) and whose weight (L) are known, is represented as resting with its lower end against the edge of a triangular file, the other end being at first supported by wooden blocks (C). A weight (W) is placed on the rule, and an india-rubber ring is passed over its end, and to this is hooked, by means of a bent pin, a thin india-rubber cord, which may be held at any desired angle, and then stretched till the lever is just lifted from the block. The distance between two knots, F and K, in the india-rubber cord is then measured, while the direction of the cord is observed by noticing at what height it cuts the rod DE of a retort-stand, which is placed on the blocks against which the file rests. The tension of the stretched cord is then measured by holding it vertically, and hanging from its end a weighed scale-pan, and finding what weight must be put in the pan to stretch the cord to the same extent as before. This weight, *plus* the weight of the pan, gives the force F, acting in the direction of the cord, that was just sufficient to lift the rule from the block. The lengths of the perpendiculars $AP_1$, $AP_2$, $AP_3$ must also be measured. Then, since the moment of a force is its magnitude multiplied by the distance of its direction from the axis, we ought to find

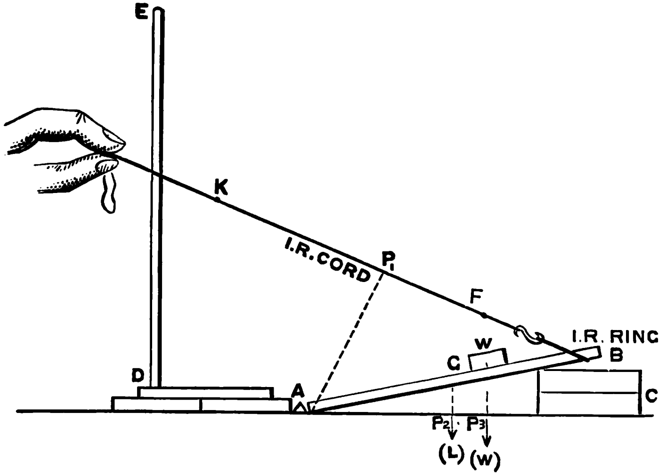


FIG. 63

$$F \times AP_1 = W \times AP_3 + L \times AP_2.$$

*N.B.*—The advantage of using an india-rubber ring at the end B is that it does not readily slip along the lever as a piece of string would, the friction between the india-rubber and the wood being greater than that between string and wood.

EXPERIMENT 9.—*Vary the last experiment by using a different weight, putting it on a different place on the lever, and raising the lever to a different inclination.*

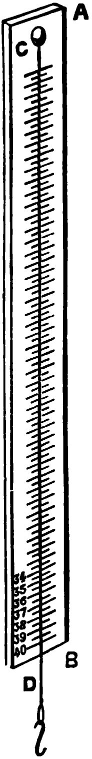


FIG. 64.

NOTE.—Since frequent use will be made in future experiments of an india-rubber cord as a dynamometer to measure forces in the manner described, it is well to have one always ready with a scale attached, as in the figure (Fig. 64).

AB is a thin strip of well-seasoned wood 40 cm. or more long, the face of which is graduated into centimetres and half-centimetres. CD is a piece of thin square india-rubber cord fastened by strong thread to a drawing-pin stuck into the wood at C.

The cord is knotted with a small tightly drawn knot in three or four places along its length, and these knots (which are not shown in the fig.) serve as marks on the cord. If a very weak force is being measured, the knot nearest the bottom should be observed and its position on the scale noted. If a stronger force is used, this knot will be drawn beyond the end of the scale, and then the position of the next knot may be observed; or if the cord be so much stretched that this also is drawn beyond the end, then the position of the next lowest, and so on for stronger forces, always using the lowest available knot.

For finding the weight which produces the same elongation of the cord when held vertically, a light cardboard scale-pan should be made, the weight of which can be easily adjusted by trimming to some convenient number of grams, *e.g.* 10 grams or 20 grams, and this weight must be added each time to the weights placed on it. This pan (with its weight written on it) can be used on all occasions. Two such dynamometers, one made with cord about 1·2 mm. in the side, and the other with thicker cord about 2 mm. in the side, will suffice for the measurement of forces varying between 15 grams and 400 grams.

It is true that the elongation produced on an india-rubber cord by a given force depends partly on the length of time for which the force is allowed to act, but the error on this account will not be important, and with care may be avoided.

EXPERIMENT 10.—*To verify by experiment the proposition called the Parallelogram of Forces, which states that "when two forces act in directions which meet in a point, and are represented in magnitude and direction by two straight lines, then they may be replaced by a single force, called their resultant, represented in magnitude and direction by the diagonal of the parallelogram of which the lines representing the two forces form the sides."*

*Instructions.*—To one end of each of two thin india-rubber cords fasten a small loop of fine string, and then hook the cords, by means of doubly bent pins, to a loop, at one end of a string, at the other end of which a weight of 100 or 200 grams is hung. Now hold the cords at an angle, as in Fig. 65, and while one boy holds them thus, let another mark off on

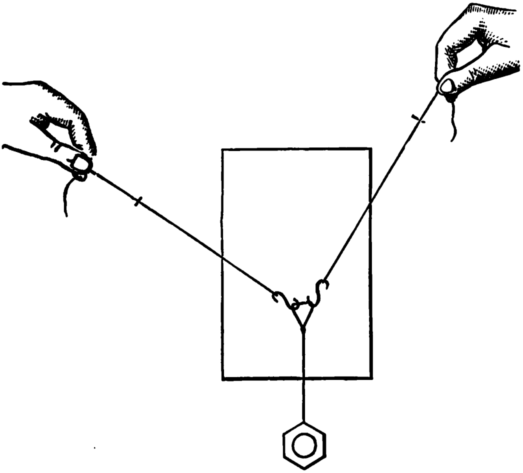


FIG. 65.

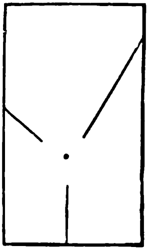


FIG. 66.

a piece of cardboard, or paper, held behind, the direction of each of the three cords, and also measure carefully, from a fine pin thrust through each cord to serve as a mark, the length to which each of the india-rubber cords is stretched.

Fig. 66 shows the paper or cardboard with the directions marked.

Now find what weights are necessary to stretch each cord to the same extent as before. This gives the force that was exerted by each india-rubber cord respectively. Then, returning to the diagram (Fig. 67), produce each line to the common meeting point O. Call their directions OA, OB, OC respectively, and let $F_1$ stand for the force acting along the india-rubber cord in the direction OA, $F_2$ that acting in the direction OB, and W for the weight acting along OC.

Our experiment has shown that the resultant of $F_1$ and $F_2$ acts in the direction C O D, and is equal to the weight (W), since it balances that weight. Now mark off along OA a length OG, representing $F_1$, and along OB a length OH, representing $F_2$, on the same scale, and along OD mark off OD to represent W on the same scale. Then OD represents what we have found by experiment to be the resultant force. Now complete the parallelogram of which OG and OH are the sides, and you will find, if your experiment has been carefully made, that OD coincides with its diagonal both in magnitude and *direction—which* shows that the proposition is true.

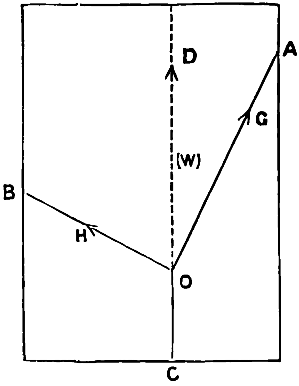


Fig. 67.

**A Proposition** of which frequent use is made in the solution of mechanical problems is the following: "When a body is at rest, since it does not move bodily in any direction, (i.) *the forces acting vertically downwards must be equal to the forces acting vertically upwards;* also, (ii.) *the forces acting horizontally in any direction must be equal to the forces acting horizontally in the opposite direction;* and since the body does not turn about any point, (iii.) *the moments of the forces tending to turn it round in any direction must be equal to the moments of the forces tending to turn it in the opposite direction.*"

**Example.**—Consider the equilibrium of a ladder resting against a perfectly smooth wall, as in the accompanying figure (Fig. 68), when the forces are

R the resistance of the ground,
F the friction of the foot,
E the elastic resistance of the wall, and
W the weight of the ladder;

and we see that, since the ladder does not move bodily up or down,

(i.) W = R;

also, since it does not move horizontally towards or from the wall,

(ii.) E = F;

and, since it does not turn about the foot,

(iii.) Moment of E about the foot = Moment of W about the foot (for F and R pass through the foot and have no moments).

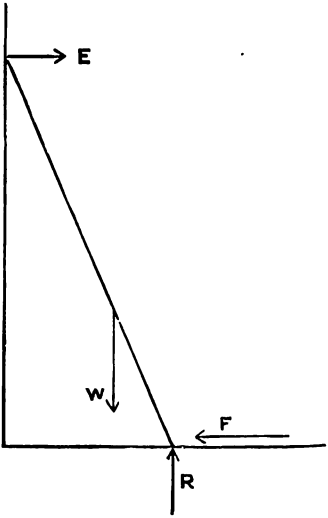


Fig. 68.

EXPERIMENT 11.—*To verify the proposition.*

*Instructions.*—Arrange the experiment as in the diagr (Fig. 69). AB is the half-metre measure, into the ends of wh pins (or drawing-pins) have been stuck as shown, to affor convenient means of attaching loops of string. CB is a t india-rubber cord hooked on to a loop of string at B, a

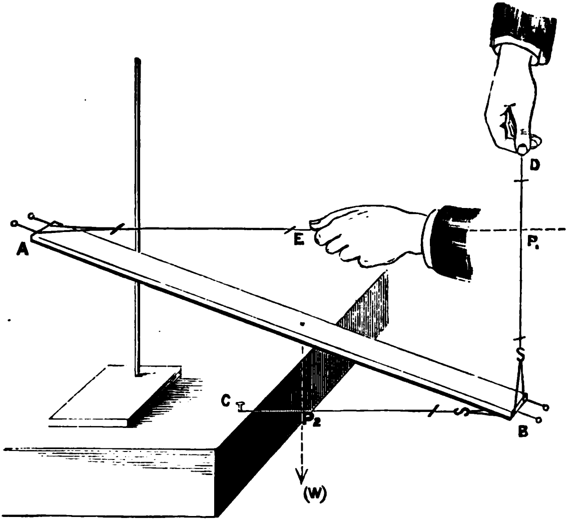


FIG. 69.

fastened to a tack in the table at C. DB and EA are simi india-rubber cords. The weight (W) of the lever and t position (C) of its centre of gravity are known. The cords a stretched, and their positions adjusted till EA and CB a horizontal and BD vertical. When in this position the leng of each cord (between two knots or fine pins thrust through to serve as marks) is carefully measured and recorded, as also the length of the perpendiculars $BP_1$ and $BP_2$. The upright rod of the retort-stand prevents the rule from swinging round. The only force acting vertically down is the weight (W) of the lever, and the only force acting vertically up is the tension of the cord BD. To show that these are equal, hang the lever from the cord, and observe that the latter is stretched to the same extent as before.

The only force acting horizontally to the right is that along AE, and the only horizontal force in the opposite direction is along BC. To show that these are equal, attach the cord AE to the cord BC, and stretch them till one is elongated as much as before; it will then be found that the other is elongated as much as before.

The lever does not turn about any point. Let us choose B as the position of an imaginary axis.

The forces along BC and BD have no turning power, since they pass through the axis. But the weight of the lever tends to turn it one way round, and the force along AE tends to turn it the other way round,

$\therefore$ The moments of these forces must be equal,

$$\therefore W \times BP_2 = \text{force along } AE \times BP_1$$

$$\therefore \text{Force along } AE = W \times \frac{BP_2}{BP_1}.$$

Now measure the force required to stretch AE to the same extent as before, and show that this is the case.

# MECHANICS—(*Continued.*)

## (2) CENTRE OF GRAVITY.

(10 *Experiments.*)

**Remarks on Parallel Forces.**—Let AB represent a rigid rod without weight, and let weights P and Q be applied to the two ends. It follows from our previous experiments that the rod will balance at some point O, in such a position that the turning power or "moment" of Q about O is the same as the turning power or "moment" of P about O,

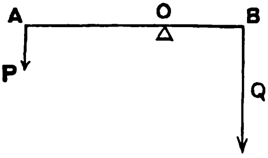


FIG. 70.

$$\text{so that } Q \times OB = P \times OA,$$

$$\text{or } \frac{OB}{OA} = \frac{P}{Q}.$$

The pressure on the fulcrum applied at O must be equal to P+Q, so that we see that the two forces of Fig. 70 are equivalent to the single force of Fig. 71, which is therefore called the resultant of the two forces.

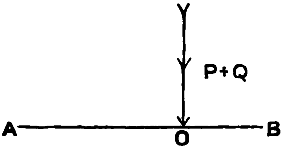


FIG. 71.

Again, if there were three parallel forces (P, Q, and R), acting at three points (A, B, and C) of a rigid system (Fig. 72), we see that P and Q will have a resultant equal to P+Q, acting

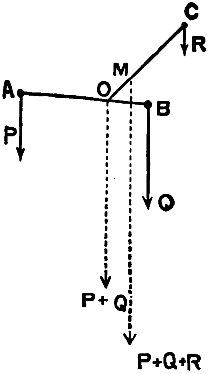


Fig. 72.

parallel to them through some point O, and this resultant and the force R will in turn have a resultant P+Q+R acting at some point M between O and C. And so on for any number of parallel forces. Now, any heavy body may be regarded as composed of an indefinitely large number of heavy particles, and what we call the *weight* of the body is the sum of the weights of the component particles. When we suspend the body by a string, or support it on a single point, we are applying a single force, equal and opposite to the resultant of all the parallel component forces that constitute the weight, and the fact that the single upward force does balance the many component downward forces, and keeps the body at rest, shows that the component downward forces *have* a single resultant. We will now show by experiment on a variety of bodies that this resultant always passes through one particular point, whatever be the position of the body. This point is known as the centre of gravity of the body.

We will take first a flat piece of cardboard of uniform thickness.

EXPERIMENT 1.—*To show in the case of a flat piece of cardboard, that, whatever be its position, the resultant of the component forces that constitute its weight always passes through a certain point.*

*Instructions.*—Stick a pin through the cardboard near one edge, and enlarge the hole a little, so that when the pin stuck horizontally into the edge of the table, the cardboard swings freely with very little friction at the hole.

When the card comes to rest the resultant force of its weight is balanced by the upward elastic resistance to bending exerted by the pin. And a plumb-line (made of a bit of lead fastened to a thread) hung over the pin will give the direction in which either force acts. Since the pin has appreciable thickness, the plumb-line must not be hung over one side, as in Fig. 73, but looped over the pin, as in Fig. 74.

In order to mark with great accuracy the direction of the plumb-line, a preliminary observation should be made, to find *whereabouts* the plumb-line cuts the lower edge of the card. This edge, in the neighbourhood of the plumb-line, should then be marked with a few parallel pencil lines near together. (See Fig. 75.) The position of the thread among these lines can be noticed with great precision, especially if the thread is made to hang quite close to, and even touching, the card.

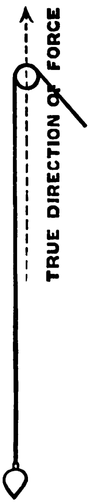


Fig. 73.

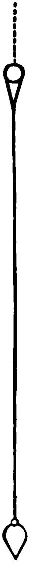


Fig. 74.

Now dismount the card, and rule on it, with a finely pointed pencil, the direction of the plumb-line. This gives the direction of the resultant of the parallel forces for one position of the card.

Now repeat the process, hanging the card from another point. This gives a second direction for a second position. This new direction cuts the old one in a point which we will call G. Now repeat a third time, and you will find that the third plumb-line cuts the first in precisely the same point as the second did, as shown in Fig. 75.

Hang up a fourth time, and you get the same result. Now place the card horizontally on a pin at the common meeting-point. You will find that it balances. You thus find that the resultant of all the parallel forces constituting the weight of the body always passes through a certain point.

*N.B.*—The centre of gravity which you have thus found does not lie *at the surface* of the card, but (if it be uniform) midway between the two opposite surfaces.

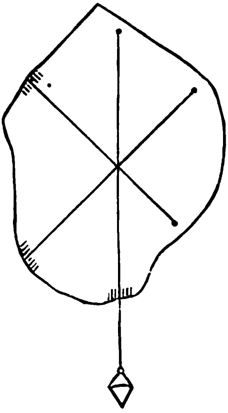


Fig. 75.

EXPERIMENT 2.—*To find the centre of gravity of a piece of wire bent once at right angles.*

*Instructions.*—Bend a piece of carefully straightened stout copper wire (size 16, say) once at right angles, making one leg about 9 cm. long, and the other exactly twice as long. Hang it up three times by the short leg, tying on the thread by which you hang it each time at a different place, and notice on each occasion the position of the point of support and the direction of the plumb-line. This may be easily done by drawing on a sheet of cardboard (or a paper block) a diagram of the wire, and hanging the wire each time against the diagram, which must be held vertically in such a position that the two coincide. The direction of the plumb-line can be marked on the diagram with a pencil, as in the previous experiment.

You will find that the third plumb-line passes through the intersection of the other two, showing not only that there is a centre of gravity, but where it is.

EXERCISE 3.—*To find the position of the centre of gravity in the last Experiment by calculation.*

*Instructions.*—The long leg alone would balance at its middle point D (see Fig. 76). The short leg would balance at its middle point E, ∴ the centre of gravity lies somewhere in the line DE.

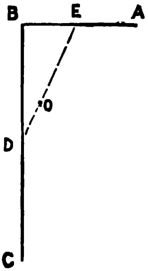


FIG. 76.

The length of BC is (say) 18 cm.

" AB is (say) 9 cm.

We may suppose that a weight of 18 units is collected at D, and a weight of 9 units at E, or 2 at D and 1 at E. To find the balancing point, mark off along DE a distance DO, equal to $\frac{1}{3}$ of DE.

Then OE is twice OD, so that

$$\text{weight at E} \times \text{OE} = \text{weight at D} \times \text{OD},$$

and ∴ the whole system will balance if supported at O.

Now turn to your diagram, and draw the line DE, measure it, and take O $\frac{1}{3}$ of DE from D. The point O should coincide with the centre of gravity already found.

In this way you can test the accuracy of the experimental determination. But it is to be observed that if one leg of the wire is thicker than the other the calculation will not

EXPERIMENT 4.—*To test the accuracy of the previous work.*

*Instructions.*—Lay the wire horizontally on a narrow straight-edge which passes just under the middle point of each leg, and see if it balances when so supported.

The upper edge of your half-metre measure when it is laid sideways against a block, as in the accompanying figure, may be conveniently used.

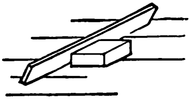


FIG. 77.

**Centre of Gravity of Geometrical Figures.**—*Definition.*—By the centre of gravity of a geometrical figure is meant the centre of gravity which the figure would have if cut out of an infinitely thin, perfectly uniform, rigid material.

EXERCISE 5.—*On the centre of gravity of a triangle.*

*Instructions.*—Cut out of uniform cardboard an accurately ruled triangle, best with unequal sides (with an area which you estimate roughly at about 100 or 150 sq. cm.). Find its centre of gravity by the method of intersecting plumb-lines—taking care, for the sake of avoiding confusion afterwards, not to make the pin-holes very near the angles. After finding the centre of gravity, prick a hole through it, and turn the card over, so as to have a clean side free of lines. Join each angle to the centre of gravity, and produce each joining line to meet the opposite side. Now show by measurements *that each of the joining lines cuts the opposite side at its middle point.* Your record should contain a lettered sketch of the triangle, and should be fashioned on the following model.

## EXERCISE 5.

### On the Centre of Gravity of a Triangle.

A triangle of the shape of ABC in the diagram was cut out of uniform cardboard, and the centre of gravity G found by the method of intersecting plumb-lines (the triangle being hung up *three* times). The three lines, AG, BG, CG, were then drawn and produced to meet the opposite sides in D, E, and F respectively.

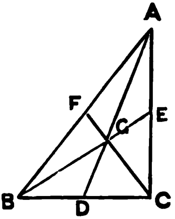


FIG. 78.

On measuring we found—

$$\left.\begin{array}{l}BD=5{\cdot}1\\CD=5{\cdot}02\end{array}\right\}\text{cm.}$$

$$\left.\begin{array}{l}CE=7{\cdot}6\\AE=7{\cdot}6\end{array}\right\}\text{cm.}$$

$$\left.\begin{array}{l}AF=9{\cdot}32\\BE=9{\cdot}3\end{array}\right\}\text{cm.}$$

which shows that D, E, and F are very nearly the middle points of the three sides.

If you made the same experiment with any number of triangles of different shapes you would obtain a like result.

EXERCISE 6.—*Now write down in your own words the rule which this result suggests for finding the centre of gravity of any triangle by simple geometry, without any experiment of cutting out and hanging up.*

EXERCISE 7.—*Centre of gravity of a triangle* (*continued*).

*Instructions.*—Now return to the card triangle, and show by carefully made and suitably recorded measurements how often the length DG is contained in DA, and how often EG is contained in EB, and how often FG is contained in FC.

The results should suggest a second rather different rule for finding the centre of gravity of a triangle.

State it in your own words.

**Centre of Gravity of a Quadrilateral.**—The centre of gravity of a plane rectilinear quadrilateral figure may be found in several ways. For example, we might find it—

(i.) Experimentally, by cutting it out of a uniform material, and then finding the centre of gravity of the figure thus cut out; or,

(ii.) By simply ruling certain lines; or,

(iii.) By a combination of geometry and arithmetic.

EXPERIMENT 8.—*To find by simple geometry the centre of gravity of a given plane rectilinear quadrilateral figure.*

*Instructions.*—Draw on a large sheet of paper a quadrilateral as nearly as you can of the shape given in the accompanying diagram, but much larger, and letter it similarly.

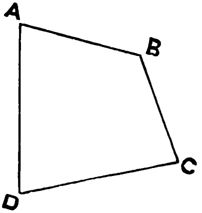


FIG. 79.

Join DB, thus dividing the figure into two triangles, and find by geometry the centre of gravity, $g_1$ and $g_2$ of each triangle; join $g_1$ $g_2$. The centre of gravity of the whole lies somewhere in the joining line. To find where, join AC, thus dividing the figure into two other triangles, and find the centre of gravity, $g_3$ and $g_4$, of each; join $g_3$ and $g_4$. Then the centre of gravity of the whole lies in the line $g_3$ and $g_4$; but it also lay in the line $g_1$ $g_2$. Therefore it lies at G, where $g_1$ $g_2$ cuts $g_3$ $g_4$.

Keep the paper with the drawing for use in the next experiment.

EXERCISE 9.—*To find the centre of gravity of the same quadrilateral by another method.*

*Instructions.*—Prick through the corners of the same quadrilateral on to a second sheet of paper, and reproduce the figure there. Now join DB, and find as before the centre of gravity, $g_1$ and $g_2$ of each of the triangles DAB and DCB respectively, and join $g_1$ and $g_2$.

Then if we consider all the weight of each triangle to be collected at its centre of gravity, we see that the whole may be regarded as a rod $g_1$ $g_2$ without weight, having a weight represented by the area of the triangle BAD at $g_1$, and a weight represented by the area of the triangle BCD at $g_2$, and the centre of gravity of the whole lies at the point where a rod so weighted would balance. To find where, measure and record the area of each triangle, and let us call the area of BAD (P), and of BCD (Q). Also measure $g_1$ $g_2$.

Then, to find the balancing point, you must divide the length $g_1$ $g_2$ into (P+Q) parts, and measure off Q of these parts from $g_1$, or P of them from $g_2$, and this will give you the balancing point, since the product P × Q = the product Q × P.

Now replace the former diagram on this one, and prick through the centre of gravity previously found, and see whether the two results coincide.

**Centre of Gravity of a Curvilinear Figure.**—The centre of gravity of curvilinear figures cannot generally be found by geometry, though in some cases, *e.g.* in the circle and the ellipse, the position of the centre of gravity is obvious from consideration of the symmetry of the figure.

Again, the centre of gravity of the semicircle ABC of the accompanying figure (Fig. 80) will evidently lie on the bisecting line AD, but it is not evident how far from D the balancing point will be.

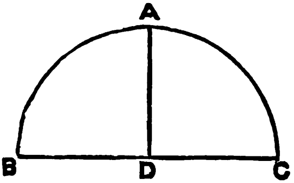


Fig. 80

EXPERIMENT 10.—*To find the centre of gravity of the semicircle in Fig.* 80.

*Instructions.*—Draw a semicircle of 10 cm. radius on a piece of uniform card. Cut it out and find its centre of gravity either by the method of intersecting plumb-lines or by balancing on a pin or a knife edge. Measure on the card the distance of the centre of gravity from the centre, and find what (decimal) fraction this distance is of the whole radius. Now measure DA, in Fig. 80, and mark off the corresponding fraction of its length, placing a small cross at the centre of gravity thus found.

## MECHANICS—(*Continued.*)

## (3) FRICTION AND INCLINED PLANE.

(14 *Experiments.*)

**Friction.**—When the surfaces of two solid bodies are in contact, and one is caused to slide over the other, the motion is resisted by the force of friction. The simplest case to study first is that of two plane surfaces in contact. For example, we will examine the friction between the lower surface of a wooden block resting on the table and the surface of the table itself.

EXPERIMENT 1.—*On the friction between two plane surfaces.*

*Instructions.*—To the middle of the end of the block (in the direction of the grain of the wood) fasten a nail, and to this attach a thin india-rubber cord; hold the cord horizontally and stretch it slightly. If the surface of the table is not very smooth, lay a writing slate on it, and place the block on this. The block in this case should be of hard wood, and not more than 3 inches in the side, and about an inch thick. The block at first does not move, because the tension of the cord is opposed by the force of friction. Now stretch the cord more; still the block does not move. The force of friction must now be greater than before, since it balances a greater force. Hence we see that (i.) *Friction is a force which can be called into play to a greater or less extent.*

Now stretch the cord gradually till the block moves. You will notice that the moment it begins to slip it moves with increasing velocity even though the slipping relaxes the cord. This shows that

(ii.) *The friction is less when there is relative motion of the two surfaces than when there is none, or that the sticking friction is greater than the slipping friction.*

EXPERIMENT 2.—*On the limit to the amount of friction.*

*Instructions.*—Now repeat the experiment several times, observing each time the length to which the cord is stretched when the block slips. You will find it to be approximately the same every time. This shows that

(iii.) *The amount of friction that can be called into play between the two surfaces has a definite maximum value.*

*N.B.*—A very slight difference in the roughness of different parts of the slate or table may make a great difference in the friction, and care should therefore be taken to lay the block each time on the same spot. Moreover, the block should be laid gently down, not pressed on to the table, since pressure will cause the surfaces to bite together more firmly.

EXPERIMENT 3.—*On the influence of the duration and closeness of contact.*

*Instructions.*—Let the block rest for some time on one spot, and then very cautiously stretch the cord. You will find that it will require a greater tension now to move the block than when it had rested but a little time on the table.

Also you will find that after pressing the block firmly on to the table (or slate) the friction is increased; showing that

(iv.) *The maximum or sticking friction increases with the amount of time that the surfaces have been in contact, and with the closeness of the contact.* The surfaces seem indeed to grow together slightly.

EXPERIMENT 4.—*On the influence of the pressure between the surfaces.*

*Instructions.*—Now put a weight on the block, and gradually stretch the cord, taking care always to hold it horizontally. You will now find that the sticking friction is increased; showing that

(v.) *The friction between two surfaces increases when the pressure between them is increased.*

EXPERIMENT 5.—*To find out the connection between the amount of friction and the pressure between the two surfaces.*

*Instructions.*—Weigh the block. Place on it a piece of lead so as to make its weight a convenient number of grams. Stretch the cord horizontally, and observe its length when the block begins to slip. Repeat four or five times, recording the length to which the cord stretches each time, so as to get the mean of several measures. Then detach the cord, and, holding it vertically, find what weights are required to produce the same elongation. (This is most conveniently done by attaching a light pan of known weight (see page 94), in which the additional weights required can be placed.)

Now repeat the experiment with a known weight on the block, finding again from the mean of several measures the value of the maximum friction (using, if more convenient, a stouter piece of india-rubber). Then repeat a third and a fourth time, using on each occasion a greater weight. Now construct a table on the following model, remembering that the pressure between the surfaces is in each case the weight of the block + the weight on the top of it.

| Pressure between the two Surfaces. | Maximum Friction. | $\frac{\text{Friction}}{\text{Pressure}}$. |
|---|---|---|
| ......... | ......... | ......... |
| ......... | ......... | ......... |
| ......... | ......... | ......... |
| ......... | ......... | ......... |

You will find that the ratio of the friction to the pressure is (approximately) constant. In other words, that

(vi.) *The Friction between two surfaces is proportional to the Pressure between them.*

**Co-efficient of Friction.**—The value of the fraction $\frac{\text{friction}}{\text{pressure}}$ is called the *Co-efficient of Friction* for the substances in question (in the present case wood and wood, or wood and slate). If the wood, either of the block or of the table, is not very hard, the increase of pressure will alter the nature of the surfaces, and the fraction $\frac{\text{friction}}{\text{pressure}}$ may vary considerably for different pressures. Moreover, it must be remembered that the friction varies with the duration of the contact, so that this last law (vi.) is only roughly correct.

EXPERIMENT 6.—*To prove* (vii.) *that if the pressure between two surfaces remains the same, then the maximum friction remains the same, even though the size of the surface of contact be altered.*

*Instructions.*—Place the block on its edge, taking care that the edge chosen has the grain of the wood the same way as the face that you have previously used; again observe the value of the sticking friction. You will find it to be (approximately) the same as when the block was laid on its side. Here the only thing altered is the size of the surface of contact.

The reason underlying this law is seen, if we imagine two similar blocks side by side on the table, each of the same weight, substance, and area. The friction of each will be the same. Now put one on the top of the other: we halve the area of contact with the table; on this account the friction is halved; but we double the pressure on the area of contact, and on this account (by vi.) the friction is doubled again.

EXPERIMENT 7.—*To prove* (viii.) *that the value of the friction between two surfaces depends on the nature of the substances in contact.*

*Instructions.*—This indeed is a matter of everyday experience. To show it, the block may be placed on a plate of glass, and the co-efficient of friction found as before. Or again, the face of the block may be oiled.

**Inclined Plane.**—When an object rests without friction on an inclined plane, the value of the force parallel to the plane required to support the object may be found graphically as follows:—

Let AB be the inclined plane, O the object on it.

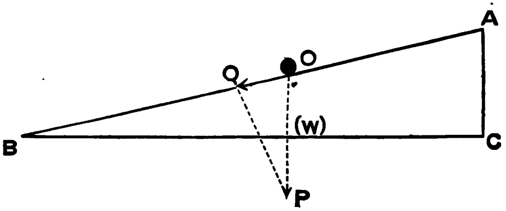


FIG. 81

Draw OP, to represent in magnitude and direction the weight (W) of the object. From P draw PQ at right angles to AB. Then, by the parallelogram of forces, OQ represents the resolved part of the weight acting along the plane, and therefore the value of the force which is needed to support the body.

Therefore the force required is less than (W) in the ratio of OQ to OP.

Or the force required $=(W) \times \frac{OQ}{OP}$,

and since the triangle OQP is similar to the triangle ACB,

$$\therefore \frac{OQ}{OP} = \frac{AC}{AB}$$

$$\therefore \text{force required} = (W) \times \frac{AC}{AB}.$$

### EXPERIMENT 8.—*On the Inclined Plane.*

*Instructions.*—To bring this to the test of experiment, make a heavy roller by sticking a stout pin through the middle of a large pill-box quite full of shot; weigh the roller when made, and call its weight (W). Loop a thread over the pin, as in the figure (Fig. 82), and hook to this a thin india-rubber dynamometer. Set the roller on an inclined plane (made of a slate or block of wood), as in the diagram, and observe the length to which the cord is stretched when held parallel to the plane. Then find, by holding the cord vertically, the weight (P) required to produce the same elongation. This gives the value of the force parallel to the face of the plane. Now measure carefully the lines AC and AB of the figure. You will find that

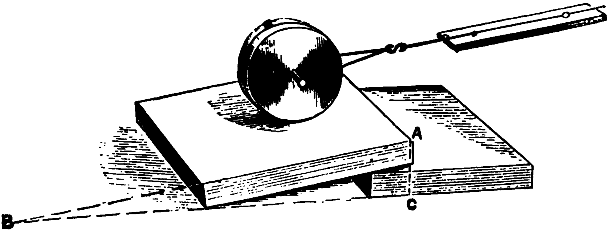


FIG. 82.

$$P = W \times \frac{AC}{AB}.$$

Now repeat the experiment with a different inclination of the plane.

*N.B.*—Just as OQ (see Fig. 83) represents the resolved part f the weight (W) acting *parallel* to the plane, so OR represents he resolved part acting *perpendicular* to the plane, *i.e.* the ressure of the body on the plane.

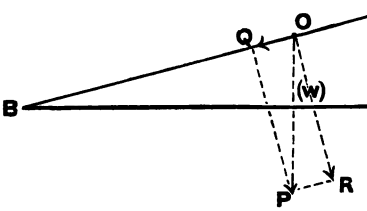


FIG. 83.

**Use of the Inclined Plane for verifying the laws f Friction.**—All the laws of friction which we have just stablished (Experiments 1 to 7) may be very easily verified y the use of the inclined plane. Thus :—

EXPERIMENT 9.—*To prove* (i.) *that friction is a force hich can be called into play to a greater or less extent; nd* (ii.) *that the friction between two surfaces is less when here is relative motion than when there is no motion.*

*Instructions.*—Place a small wooden block on a slate, nd slowly tilt the latter. You will observe that only when the inclination reaches a certain value does the block begin to slide, proving (i.); but that it then slips with increasing velocity, proving (ii.).

*Definition.*—The inclination of the plane to the horizon when the slipping begins is called the "angle of repose."

EXPERIMENT 10.—*To prove* (iii.) *that the amount of friction that can be called into play between two surfaces has a definite maximum value.*

*Instructions.*—It is only necessary for you to observe that when you repeat the experiment several times, the inclination at which slipping begins is (approximately) constant. The elevation of the higher end of the slate may be conveniently observed against the rod of the retort-stand.

EXPERIMENT 11.—*To show* (iv.) *that the maximum or sticking friction increases with the amount of time that the surfaces have been in contact and with the closeness of the contact.*

*Instructions.*—Let the block be pressed firmly on the slate, or let it rest for some time on the same spot of the slate, and en tilt the latter very gradually. You will find that it now quires a greater inclination, and therefore a greater resolved ce along the plane, to cause slipping.

EXPERIMENT 12.—*To show* (v.) *that the friction between two surfaces increases when the pressure between them is increased; and* (vi.) *that the friction is proportional to the pressure.*

*Instructions.*—It is only necessary to weight the block, and again tilt the plane, when you will find the angle of repose to be approximately unaltered. Now, as long as this angle is the same, the ratio of OQ to OR (see Fig. 83), *i.e.* of the friction to the pressure, is the same, so that the experiment shows that by increasing the weight of the block, and therefore the pressure on the plane, we increase the friction in the same proportion.

*N.B.*—Since the value of the ratio $\frac{\text{friction}}{\text{pressure}}$ is called the co-efficient of friction, we see that

$$\text{co-efficient of friction} = \frac{OQ}{OR} = \frac{AC}{CB}.$$

Experiment 13.—*To prove* (vii.) *that if the pressure between two surfaces remains the same, then the maximum friction remains the same even though the size of the surface of contact be altered.*

*Instructions.*—It is only necessary to place the block on its edge instead of on its face (taking care that the grain of the wood is in the same direction as before), and you will find the angle of repose (approximately) unaltered.

Experiment 14.—*To show how* (viii.) *the friction depends on the nature of the surfaces in contact.*

*Instructions.*—Find the co-efficient of friction of wood on wood, of clean glass on clean glass, then of oiled glass on oiled glass, by measuring AC and CB in each case (see Fig. 83).

# MECHANICS—(*Continued.*)

## (4) FRICTION OF CORDS AND USE OF PULLEYS.

(4 *Experiments.*)

**Friction of a Cord.**—When a cord, along which a tension is applied, has its direction altered by passing round any object, there is always more or less friction at the bend between the cord and the object.

EXPERIMENT **1.**—*On the friction of a cord.*

*Instructions.*—Hang a weight of 100 grams vertically from a thin india-rubber dynamometer by a smooth string, and observe the elongation produced. Then hold your half-metre rule horizontally, so that the string makes a slight bend at its edge, as in position (1) of the accompanying figure (Fig. 84). You will now find that you can relax the india-rubber somewhat, without the cord slipping, since the weight is now partly balanced by the friction. On the other hand, in order to raise the weight, you must exert an increased tension, since no motion will be produced till the tension overcomes both the weight and the friction.

Now lower the hand which holds the dynamometer, so that the cord takes the positions (2), (3), (4), etc. You will notice that, as the sharpness of the bend increases, so does the friction; *i.e.* smaller and smaller tension of the india-rubber being re[illegible] sustain the weight. Finally, wrap the string once or even twice or thrice round the measure, when you will probably find that the friction alone is sufficient to sustain the weight.

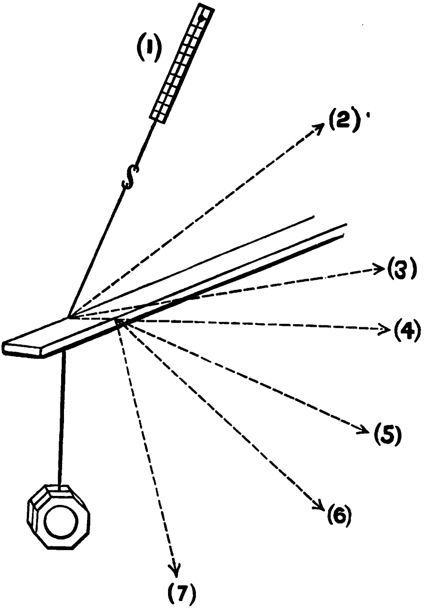


Fig. 84.

EXPERIMENT 2.—*Friction of a cord* (*continued*).

*Instructions.*—Make a similar experiment, using, instead of the metre rule, a piece of round glass tube, and find out for yourself whether the friction is greater when the string passes round a wide tube (*e.g.* a wide test-tube), or when it passes round a narrow tube. Describe fully the way you make the experiment.

**Use of a Pulley in diminishing the effect of friction at a bend.**—A fixed pulley is of great use in diminishing the effect of friction at a bend; for, since the

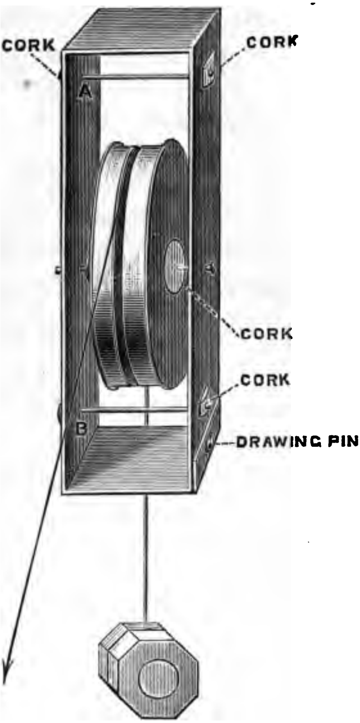


Fig. 85.

axle is of small diameter, the friction exerted at its circumference has but a small moment, and is overbalanced by the plication of a very slight force at the circumference of the ley.

EXPERIMENT 3.—*Test the effect of friction with the pulley given you,* (1) *with the two branches of the string at right angles to each other,* (2) *with the two branches parallel to each other.*

*N.B.*—A pulley is easily made for this experiment out of a large flat pill-box mounted in a stout cardboard frame, as in the figure (Fig. 85). The axle is made of a very stout pin, and turns with the box in holes made with a small brad-awl in the frame; and the box is prevented from sliding on the axle by two conical bits of cork as shown. The groove of the pulley is obtained by half opening the box. The pins A and B are to give rigidity to the frame, of which the overlapping corner is held by a drawing-pin.

**Moveable Pulleys.**—A single moveable pulley, arranged as in the diagram (Fig. 86), enables the tension of the string ABC to be used twice instead of once in supporting the weight

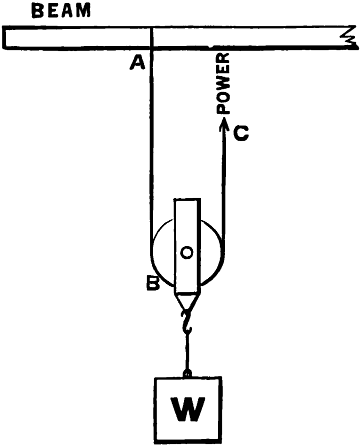


FIG. 86.

(W), so that half the weight is borne by the beam, and half only needs to be balanced by the power applied at C.

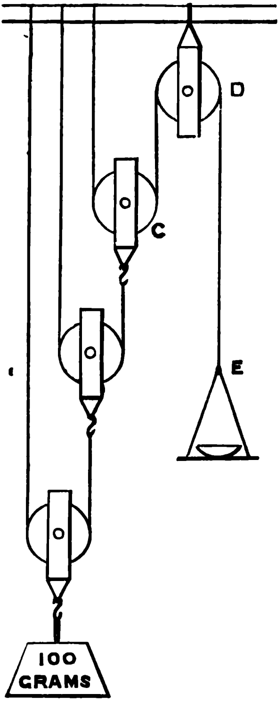


Fig. 87.

EXPERIMENT 4.—*Use of several moveable pulleys.*

*Instructions.*—Arrange three moveable and one fixed pulley in the manner shown in Fig. 87. Attach a light cardboard pan to the cord CDE, and balance the pulleys by means of a watch-glass of shot placed in the pan. Then hang from the lowest pulley a weight of 100 grams. You will find that it is balanced by 12·5 grams placed in the pan. Explain why in your own words.

# PART V.

# ELASTICITY.

(20 *Experiments.*)

# PART V.

# ELASTICITY.

## EXPERIMENTS ON ELASTICITY.

**Definitions.**—A *Force* may be defined as that which produces, or tends to produce, motion; or which stops, or tends to stop, the motion of matter already moving.

By the *Weight* of a body we mean the amount of force with which it is attracted towards the earth.

Whenever a body is at rest, either no external forces act upon it, or, the forces which act are equal and opposite.

The *Elasticity* of a body is its power of recovering, more or less completely, its original form, after having been in any way distorted: for example, stretched, compressed, twisted, or bent.

By the *Force of Elasticity* we mean the force exerted by the body, at any moment, in its endeavour to recover its original form. We shall generally speak of it as the *force of recovery.*

This force of elasticity enters into all mechanical phenomena. For example, whenever a heavy body is mechanically supported in any way, the force which balances its weight is the force of elasticity. Thus when a book is placed on a table, the table bends slightly under the weight of the book until the elastic force which it exerts, in the endeavour to recover itself, is equal to, and balances the weight of, the book. If the book were heavier, the table would have to bend more l the force of recovery became equal to the weight of the

We cannot as a rule see the table bend, but a few e ments will convince you that it does.

EXPERIMENT 1.—*Preliminary examination of the be of laths.*

*Instructions.*—Place a lath horizontally on two sup as in Figure 88; the edges of two triangular files la blocks form very convenient supports.

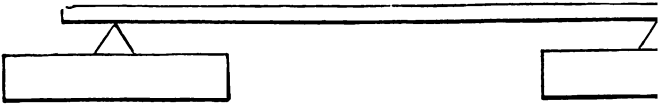


FIG. 88.

Then place a weight on the lath midway betwee supports, sufficiently great to bend it considerably.

Now shorten the distance considerably between th ports, and again put on the weight. The result show the amount of flexure produced depends on *the d between the supports.*

Now take a lath of different thickness, say one that twice as thick, but in other respects the same, an on the same weight, the supports being as far apart the first Experiment. The flexure will be much less. shows that the flexure depends on *the thickness of the lat*

Now take a lath of the same thickness as the first, double the width, or, what is the same thing, lay by th of the first a second similar one, and rest the weight e on both. The result shows that the flexure depend on *the width of the lath.*

Now take a lath of the same dimensions as the first, but of a different material, support it in the same way, and put on the same weight as in the first Experiment. The result will show *the influence of the material.*

It is now evident that the reason why the flexure of a table is not generally evident when a book is laid on it lies in the thickness, the breadth, or the rigidity of the material of which it is made.

It is evidently a matter of interest to endeavour to find out whether there is any invariable connection between the flexure which a given weight produces, and the length, the breadth, and the thickness of the lath; and again, whether there is any connection between the amount of the bending weight, and the amount of flexure it produces. For if we can find such a connection, it may enable us, after making a single experiment with a particular rod of any material, to prophesy about any other rod of the same material, of any given length, breadth, and thickness, to what extent it would be bent by a given weight. And it is always interesting to be able to make such prophecies, and in Engineering extremely important.

We will examine each point in turn, and will begin first with the last mentioned.

EXPERIMENT 2.—*To find out the connection between the bending weight and the flexure produced by it, by placing different weights on the same lath, and measuring the deflection produced by each in turn.*

*Instructions.*—For a lath you may use one of the metre measures. Support it horizontally on the edges of two triangular files, raised by means of blocks 4 or 5 cm. above the table. Place the files at first 50 cm. apart. First measure very carefully the height above the table of the lower surface of the lath at its middle point, using for this the half-metre measure, and estimating the tenths of millimetres. Enter this height in the rough note-book as $H_0$. Now place a weight of 200 grams at the middle (it is best to place the weight on its edge, and not to let it overhang on the side where you measure), and measure the height again. Enter this height as $H_1$. Now increase the weight to 400 grams, and enter the height as $H_2$, and so on, increasing the weight each time by 200 grams till (say) 1200 grams are reached. The record should appear as follows :—

### Experiments on Elasticity of Flexure.

Length of rod between points of support = 50 cm.
$H_0$ with no weight in the middle = — ,,
$H_1$ ,, 200 grams ,, — ,,
$H_2$ ,, 400 ,, ,, — ,,
$H_3$ ,, 600 ,, ,, — ,,
$H_4$ ,, 800 ,, ,, — ,,
$H_5$ ,, 1000 ,, ,, — ,,
$H_6$ ,, 1200 ,, ,, — ,,

Great care must be taken before making the measures that the blocks carrying the supports rest firmly on the table, and that they do not tilt when a weight is applied.

To see the full significance of your result, you must now subtract each height from the original height, so as to obtain the flexure produced by each weight. This will give you the following table :—

Flexure produced by 200 grams = . . . . cm.
,, ,, 400 ,, = . . . . ,,
,, ,, 600 ,, = . . . . ,,
,, ,, 800 ,, = . . . . ,,
,, ,, 1000 ,, = . . . . ,,
,, ,, 1200 ,, = . . . . ,,

On inspecting this table, you will find, if your measures have been accurately made, that by doubling the weight you have doubled the flexure, by trebling the weight you have trebled the flexure, and so on, until the flexure begins to get very great, when the table will show that an increase of weight produces more than a proportional increase of flexure: thus the flexure produced by 1200 grams will probably be considerably more than six times that produced by 200 grams, or three times that produced by 400 grams.

But the result that is of importance to us is the first, namely, that, *as long as the lath is but little bent, the flexure is proportional to the bending weight.*

EXPERIMENT 3.—*To find the connection between the length of the lath and the flexure.*

*Instructions.*—To do this we must take several laths of the same material, breadth, and thickness, but of different lengths, and apply to each the same bending weight, and observe the flexure in each case; or, what is the same thing, we may use the same lath several times, with the supports at a different distance apart each time.

Use the metre measure or a similar lath as before, but with the supports 90 cm. apart, taking every precaution to secure the immobility of the supports. Then measure and record the height of the centre of the rod above the table. Now place on it a weight which does not bend it beyond the limit for which our former result holds good, and measure again the height above the table. By subtracting the latter measure from the former you obtain the flexure produced.

Now repeat with the supports 75 cm. apart, and then again with the supports 50 cm. apart. Record the results in the following manner:—

| Length of Lath. | Height of centre to start with. | Height of centre when bent by . . . gram weight. | Flexure. |
|---|---|---|---|
| 90 cm. | . . . cm. | . . . cm. | . . . cm. |
| 75 ,, | . . . ,, | . . . ,, | . . . ,, |
| 50 ,, | . . . ,, | . . . ,, | . . . ,, |

If you find that the flexure, when the supports are but 50 cm. apart, is so small that you cannot accurately measure it, you may use double the weight and *halve* the flexure produced by it, since we have found that the flexure is proportional to the weight.

On inspecting the last column, you will find that, though the flexure diminishes with the length, yet it does not diminish in the same proportion. For if you divide the first length by the third length, you get the ratio of the lengths, *i.e.* $\frac{90}{50}=\frac{9}{5}=1{\cdot}8$, and if you divide the first flexure by the third, you get the ratio of the corresponding flexures, and the number is not at all the same.

If, however, instead of finding the ratio of the lengths, you find the ratio of the *squares* of the lengths, *i.e.* if you take the value of $\frac{90^2}{50^2}=\frac{9^2}{5^2}=\frac{81}{25}=3{\cdot}24$, you perceive that this number is more nearly equal to the ratio of the flexures. Now try in the same way the ratio of the cubes of the lengths, *i.e.* the ratio $\frac{90^3}{50}$. This you will find, if your measures have been well made, is very nearly equal to the ratio of the flexures. Now this looks like the connection that we are seeking. In order to test it, find the ratio between the first flexure and the second, and then the ratio of the cube of the first length to the cube of the second length, *i.e.* the value of $\frac{90^3}{75^3}$. If this ratio is the same as that of the flexures, it will show that we have now found what we want. And the result may be stated in the following words: *When two laths of the same breadth, thickness, and material, but of different lengths, are bent by the same weight, then the flexure of the second is to the flexure of the first as the cube of the length of the second is to the cube of the length of the first (provided that neither is very much bent).*

**Influence of Breadth.**—We will now examine the influence of the *breadth* of the lath. It is evident what this will be. For if two similar rods were placed side by side, and one were bent by a force of 200 grams, it would require an additional 200 grams to bend the second to the same extent, and if we always put the same weight on each, they will bend together, and behave like one broad rod; so that we see that a rod twice as broad will require double the weight to bend it to the same extent; a rod three times as broad three times the weight, and so on. In other words, the elastic resistance called out by a given amount of flexure is proportional to the breadth of the rod.

EXPERIMENT 4.—*To find the influence of the thickness of the lath.*

*Instructions.*—For this purpose three laths are given you, which have been cut from the same board, and then carefully planed down, so that the second is twice as thick as the first, and the third two and a half times as thick, the breadth and length being the same in all three. To make the experiment you must keep the supports at the same distance apart, and measure the flexure produced by the same weight in each case, recording the result in a suitable table. The larger the weight used the more measurable will be the flexure, but care must be taken not to use a weight so great that it bends the lath beyond the limit for which the result of Experiment (2) holds good.

The result will show that the ratio of the flexure produced in the first case to that produced in the third case is not the same as the ratio of the third thickness to the first, *i.e.* is not the same as $\frac{2\frac{1}{2}}{1} = 2{\cdot}5$. If, however, you try the ratio of the squares of these numbers, *i.e.* of $(2\frac{1}{2})^2 : 1^2$, you will find that its value agrees more nearly, while, if you try the ratio of the cubes of the thicknesses, *i.e.* the ratio $\frac{(2\frac{1}{2})^3}{1^3}$, you will find that it is very nearly the same as the ratio of the flexures.

In order to test this result, you can find the value of the ratio of the first flexure to the second, and compare with this the ratio of the cube of the first thickness with the cube of the second. If the two ratios are nearly equal, the fact will point to the following result: *That when the same bending weight is applied to two different laths of the same material, length, and breadth, but of different thickness, then the flexure of the second is to the flexure of the first as the cube of the thickness of the first is to the cube of the thickness of the second (provided that neither is much bent).*

**Numerical Examples.**—We can now solve such questions as the following:—

**Example 1.**—A rod 4 feet long, 1 inch broad, and $\frac{1}{2}$ inch thick is bent $\frac{1}{10}$ inch by a weight of 20 lbs.: what would be the flexure produced by a 4 lb. weight on a rod 6 feet long, 2 inches broad, $\frac{5}{8}$ inch thick?

The answer may at once be given thus:—

On account of the diminution of weight from 10 lbs. to 4 lbs., the flexure will be diminished in the ratio $\frac{4}{10}$.

On account of the increase of length from 4 feet to 6 feet, the flexure will be increased in the ratio $\frac{6^3}{4^3}=\frac{27}{8}$.

On account of the increase of breadth from 1 inch to 2 inches, the flexure will be diminished in the ratio $\frac{1}{2}$; and on account of the increase in thickness from $\frac{1}{2}$ inch to $\frac{5}{8}$ inch, the flexure will be diminished in the ratio of $\frac{(\frac{1}{2})^3}{(\frac{5}{8})^3}=\frac{64}{125}$,

$\therefore$ Flexure required will be $\frac{1}{10}$ inch $\times\frac{4}{10}\times\frac{27}{8}\times\frac{1}{2}\times\frac{64}{125}=\cdot 0346$ in.

**Example 2.**—A beam 15 feet long 4 inches broad and 3 inches in vertical thickness is bent 1 inch by a weight of 100 lbs. placed at its centre. How thick must a beam of the same material, 12 feet long and 6 inches broad, be that a weight of 500 lbs. may bend it two inches?

Let $x$ be the thickness required.

Then, as before—

On account of the change of thickness from 3 inches to $x$, the flexure is changed in the ratio of $\frac{3^3}{x^3}$; on account of the diminution of length from 15 feet to 12 feet, the flexure is diminished in the ratio of $\frac{12^3}{15^3}$; on account of the increase of breadth from 3 inches to 6 inches, it is diminished in the ratio of $\frac{3}{6}$; and on account of the increase of the weight from 100 lbs. to 500 lbs., the flexure is increased in the ratio of $\frac{5}{1}$,

$$\therefore \text{The flexure} = 1 \text{ inch}\times\frac{3^3}{x^3}\times\frac{12^3}{15^3}\times\frac{3}{6}\times\frac{5}{1}.$$

And if this is to be 2 inches, we must have

$$1\times\frac{3^3}{x^3}\times\frac{12^3}{15^3}\times\frac{3}{6}\times\frac{5}{1}=2, \text{ or } x^3=17\cdot 28,$$

$$\therefore x=\sqrt[3]{17\cdot 28}=2\cdot 585 \text{ inches.}$$

**Tension and Compression.**—The flexure of a lath evidently involves the stretching of the material on the outside of the bend, and the compression of it along the inside. Thus in the bent lath, represented in the figure (Fig. 89), the matter along AB is stretched, while that along CD is compressed, so that the elasticity under flexure involves the more simple cases of elasticity under compression and elasticity under tension.

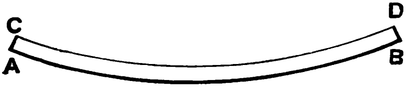


FIG. 89.

The study of elasticity under tension and under pressure is, however, not quite so easy as under flexure, for most substances, such as wood, iron, glass, etc., if made into a bar or wire, and then stretched by a weight hung to the lower end, *break* before the elongation is great enough to be easily measured; nor is the compression of such substances easily rendered visible.

**Laws of Elasticity of Tension and Compression.**—It can however be shown by suitable experiments that when a bar of any given substance is stretched or compressed, the amount of elongation or compression is (i.) proportional to the stretching or compressing force; (ii.) proportional to the length of the bar; (iii.) inversely proportional to the sectional area of the bar, provided always that the elongation or compression is not so great, but that the bar completely recovers itself.

EXERCISE 5.—*As an exercise, to test whether you have thoroughly understood the experiments on Elasticity of Flexure, explain clearly how you would proceed to establish, in turn, each of the above-mentioned points, with reference to the elasticity of tension of some substance, say steel.*

*Also explain, if you can,* THE REASON *of* (ii.) *and* (iii.).

**Oscillations of Elastic Bodies.**—When an elastic body is distorted and then let go, it generally performs a series of oscillations in its endeavour to recover its original form. Thus, if a weight be attached to the lower end of a spiral spring, and then pulled and let go, it returns to the position of rest, but with a velocity which carries it beyond that position; then it descends again, but not quite so far as at first. In this way it performs, in coming to rest, a series of oscillations, each of which is rather smaller in extent than that which preceded it.

When, after being released, the weight has passed to the other side of the position of rest, and then back again to the starting-point, it is said to have performed a *complete oscillation.*

EXPERIMENT 6.—*Make the experiment.*

**Torsion.**—Similarly, if a weight be firmly attached to the lower end of a thin wire, and then twisted round and let go, the wire will twist back again to its position of rest, and beyond, and then back again, and so on. When, after being released, it has twisted to the other side and back again, it is said to have performed a *complete oscillation.*

EXPERIMENT 7.—*Make the experiment.*

**Definition.**—By the *amplitude* of an oscillation is meant the measure of the swing from the final position of rest to one side or other of that position. In the case of the twisted wire, the amplitude is measured by the *angle* through which the weight is twisted. One of the most familiar examples of an oscillating body is a pendulum. Here, again, the amplitude of the oscillation is measured by the angle through which the pendulum swings to one side or other of the position of rest.

**Proposition.**—Now, it can be shown, both mathematically and by experiment, that *if the force of recovery is at every moment proportional to the distortion or displacement, then the oscillations will be isochronous,* i.e. *of the same duration, whether they be great or small.*

The object of the experiments which follow is to familiarise you with this proposition, which is of great importance in physics, and to convince you of its truth.

We will first take the case of a weight hung from the end of a spiral steel spring.

EXPERIMENT 8.—*Experiment to show that the oscillations of a spiral steel spring in recovering itself after being stretched are isochronous, whether they be of great amplitude or small, provided that it be not stretched beyond the point of complete recovery.*

*Instructions.*—To the bottom of the spiral steel spring given you attach a weight sufficient to increase its length by about one-half. Pull down the weight so as to stretch the spring considerably, but not so much but that it completely recovers itself: let it go, and observe by a watch or clock the time of say forty (or fifty) complete oscillations. Record the result, and repeat, if necessary, to make sure. Now do the experiment again, but this time stretching the spring very little before you let go, so that the amplitude of the oscillations is very small. You will find, however, that the duration of forty (or fifty) oscillations is the same as before.

EXPERIMENT 9.—*Experiment to show that the oscillations of a wire under the influence of torsion are isochronous, whether they be of great amplitude or small, provided the wire be not so much twisted that it takes a permanent "set," and does not completely recover itself.*

*Instructions.*—From a thin steel wire (about size No. 26), and at least 1 metre or 1½ metres long, suspend a weight of say a kilogram. Make a mark on the face of the weight, then twist it round through two or three complete revolutions, and observe whether it comes to rest in the old position: if not, you must not twist it so far. Now, as in the previous experiment, observe the duration, first of a certain number of oscillations of large amplitude, and then of the same number of oscillations of very small amplitude—only a few degrees: you will find them to be very nearly isochronous.

EXPERIMENT 10.—*To show that the oscillations of the prongs of a tuning-fork are isochronous.*

*Instructions.*—In this case we may indeed just *see*, by its hazy outline, that the fork is oscillating when first struck, but the oscillations are too rapid to count with the eye. By means of the ear, however, we can tell that the vibrations are exactly isochronous: for if we sound the fork, and hold its stem on the table, which then serves as a sounding-board, we observe that, as the note dies away, it *does not alter in pitch:* and we know that the pitch of a note depends on the number of pulses which reach the ear per second.

EXPERIMENT 11.—*To show that the oscillations of a pendulum are isochronous, provided that the amplitude of swing is never very great.*

*Instructions.*—Make a pendulum of a heavy weight fastened to the end of a string, a metre or more in length: draw the weight aside, so that the new position of the pendulum makes an angle of say twenty degrees with the original position, and observe the number of oscillations performed in a minute.

Then repeat the experiment, but with an amplitude of oscillation that is very small. You will find that the number of oscillations per minute is the same as before.

EXPERIMENT 12.—*To show that the oscillations of a stretched india-rubber cord are* NOT *isochronous.*

*Instructions.*—Attach to an india-rubber cord, 20 or 30 cm. long, a weight sufficient to stretch it to about four times its original length—a piece of cord, from 1 to 2 mm. thick, of square section, will do very well; and observe, just as with the spiral spring in Experiment 8, the duration, first of a certain number of large, and then of the same number of small, oscillations. You will find that the large oscillations are slower than the small ones.

**Summary of Results.**—We have now examined five cases of an oscillating body. In the first four, viz. the stretched spring, the twisted wire, the tuning-fork, and the pendulum, we found the oscillations to be isochronous. In the case of the india-rubber cord they were not isochronous. We will now show that, where the oscillations are isochronous, the force of recovery is exactly proportional to the distortion, while in the last case it is not so.

EXPERIMENT 13.—*To show that the force of recovery exerted by the stretched spring is exactly proportional to the elongation.*

*Instructions.*—Hang a scale-pan from the bottom of the spring, and fix upright against it your metre measure, so that the pan just touches it, as in the figure (Fig. 90). Observe and record the height of the edge of the pan on the scale. Now add a weight sufficient to stretch the spring 3 or 4 cm., and again observe and record the

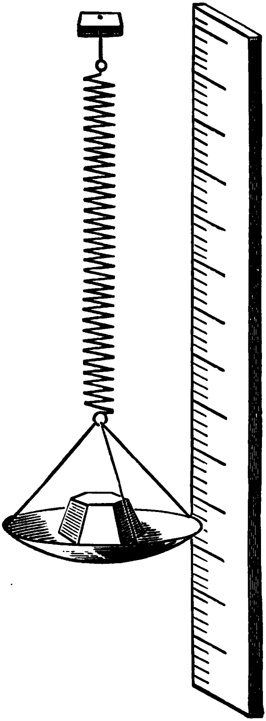


FIG. 90.

level of the pan. Now repeat, with double the weight on the pan, treble the weight, and so on, taking care to notice each time whether the spring completely recovers itself on the removal of the weight. Continue in this way till it appears unsafe to stretch the spring further. You will now find, on examining your record, that the first weight, which we may call (W), produced an elongation of . . . cm.; the second weight (2W) produced an elongation twice as great; the third (3W) produced an elongation three times as great, and so on. Now the stretching weight is the measure of the force of recovery, since it is this latter that balances the weight. Hence it follows that the force of recovery is at every moment proportional to the elongation. The record should be made on the model of that which follows.

OBSERVATIONS OF THE ELONGATION OF A SPIRAL STEEL SPRING PRODUCED BY INCREASING WEIGHTS.

Height of pan at starting = 38·4 cm.

| Stretching Weight. | Height of Pan. | Elongation. |
|---|---|---|
| 200 grams. | 42·6 cm. | 4·2 cm |
| 400 ,, | 47·0 ,, | 4·2 + 4·4 = 8·6 ,, |
| 600 ,, | 51·3 ,, | 8·6 + 4·3 = 12·9 ,, |
| 800 ,, | 55·6 ,, | 12·9 + 4·3 = 17·2 ,, |

*N.B.*—Great care must be taken to place the weights each time exactly in the middle of the pan, otherwise the edge will be tilted and a large error may be introduced. Before making the experiment, practise replacing the same weight two or three times in the pan, till you can with certainty reproduce the same reading on the scale each time.

EXPERIMENT 14.—*To show that in the case of the tuning-fork the force of recovery is proportional to the distortion.*

Here what we desire to show is that the pressure which is required to cause the prongs to approach each other by a distance of say one-tenth of a millimetre, is half that which will produce an approach of two-tenths, and so on. It is evident that the difficulty of the experiment will lie in measuring the very small amount of approach with accuracy. This difficulty may be surmounted in the following manner:—

*Instructions.*—Lay the tuning-fork on the table as in the figure (Fig. 91), with its ends projecting a little over the edge,

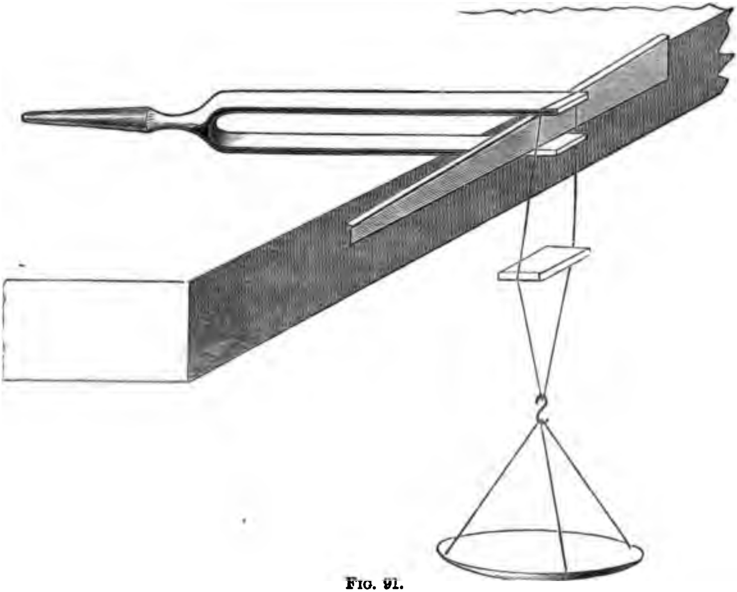


FIG. 91.

and hang a scale-pan by means of a loop of string from the upper prong, keeping the string from touching the lower for measuring the displacement of the bob. Now draw aside the bob by means of the cord (as in Fig. 94) to a distance

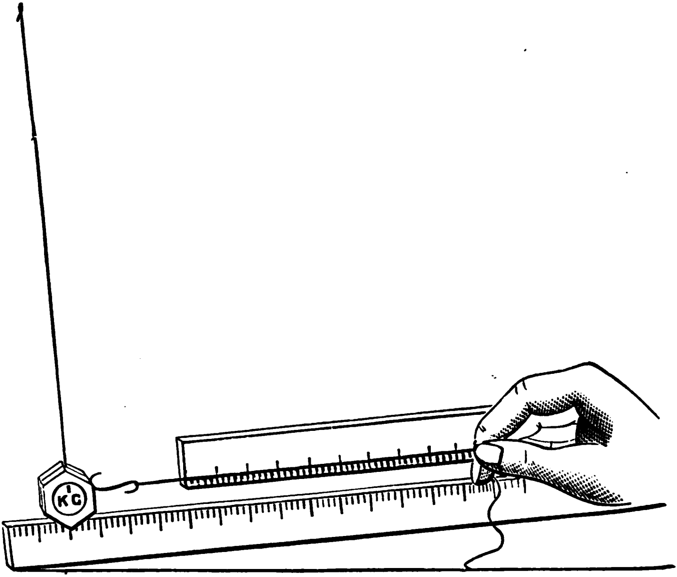


FIG. 94.

of say 10 cm., taking care to keep the cord at right angles to the pendulum, and measure carefully, with a second metre scale,[1] the length to which the cord stretches from the point at which you hold it with your fingers. Now detach the cord, and hang on a weighed balance pan, and add weights till the cord is stretched to exactly the same extent. These weights her with the weight of the pan) measure the force of ry for a displacement of 10 cm.

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[1] **The dynamometer described in the note, p. 94, may be used with advantage here.**

v repeat the operation, but this time drawing the bob o a distance of 20 cm., and measure as before the length stretched cord. You will now find that the weight ed to produce the same elongation is double as great as , which proves that the force of recovery is double as and in the same way you will find that a displacement bob of 30 cm. is attended by a of recovery three times as great first. So that in each case the of recovery is proportional to the cement.

B.—It is not necessary to hold the ubber cord at the same place on ccasion ; indeed when it is much ned a shorter length is more connt.

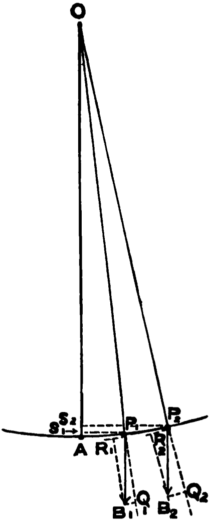

FIG. 95.

**ometrical Proof.**—The same can be obtained geometrically as s :—

OA be the pendulum in its position of rest,
$OP_1$ its position when drawn aside a few degrees,
$OP_2$ its position when drawn aside twice as far.

w from $P_1$ and $P_2$ equal vertical lines, $P_1B_1$, and $P_2B_2$, to ent the weight of the bob. This weight is a force that e resolved into two—one PL, in the direction of the n of the pendulum, and only tending to stretch it, balanced by the elastic resistance to stretching, and the other, PR, at right angles to the pendulum, and acting as the force of recovery. Now it is easy to show that the line $P_2R_2$, which represents the force of recovery in the second case, is double of the line $P_1R_1$, which represents it in the first case.

Draw $P_1S_1$ and $P_2S_2$ meeting OA at right angles, and let the length of the pendulum be $l$, and let $P_1B_1$ $(=P_2B_2)=W$.

Then the triangle $B_1P_1R_1$ is similar to the triangle $P_1OS_1$
and „ $B_2P_2R_2$ „ „ „ $P_2OS_2$

$$\therefore \frac{P_1R_1}{W}=\frac{P_1S_1}{l}, \text{ and}$$

$$\frac{P_2R_2}{W}=\frac{P_2S_2}{l},$$

$$\therefore \frac{P_2R_2}{P_1R_1}=\frac{P_2S_2}{P_1S_1}=\frac{\text{arc } AP_2}{\text{arc } AP_1} \text{ (so long as the angle } AOP_2 \text{ is small),}$$

$$\therefore \frac{\text{Force of recovery in second case}}{\text{Force of recovery in first case}}$$

$$=\frac{\text{Displacement in second case}}{\text{Displacement in first case}}. \qquad \textit{Q.E.D.}$$

Exercise 16.—*As an exercise, draw the figure on a large scale, and measure* $P_2R_2$ *and* $P_1R_1$.

**Meaning of small Oscillations.**—You will now see the significance of saying that the oscillations of a pendulum are isochronous only when the amplitude of swing is small, for it is evident that when the amplitude is great the force f recovery does not keep proportional to it. Thus let OA the position of rest of the pendulum, $OP_1$ its position displaced $22\frac{1}{2}$°, $OP_2$ its position when displaced 45°, position when displaced 90°. It is evident that

---

[1] The dy
advantage here

$P_2S_2$, to which the force of recovery is proportional, is not now double of $P_1S_1$, still less is $P_3O$ double of $P_2S_2$. Hence we see that when the displacement is large, the force of recovery is not so great as it should be to produce isochronous oscillations. Consequently oscillations of great amplitude will be slower than those of small amplitude.

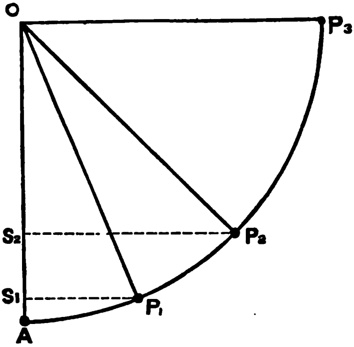

FIG. 96.

EXPERIMENT 17.—*Show by experiment that this is the case.*

EXPERIMENT 18.—*To show that in the case of a stretched india-rubber cord the force of recovery is* NOT *proportional to the elongation, but is relatively weaker the more the cord is stretched; also, that the cord, after being stretched, does not at once completely recover itself.*

*Instructions.*—Proceed precisely as in Experiment 13, with the stretched spring, but using a stout india-rubber cord, and continuing to add weights till it seems likely to break. Your results will show, if properly recorded in a tabular form, that in order to evoke double, or treble, the force of recovery produced by the first weight, the elongation must be much more than double or treble as great; in other words, the force of recovery does not keep pace with the elongation, but grows relatively weaker the more the cord is stretched. This explains why the large oscillations took longer time than the smaller ones (see Experiment 12, p. 140). The force of recovery when the cord was much stretched was not so great as it should have been to produce isochronous oscillations. Consequently the weight was moved too slowly, and the oscillations took a longer time.

Also you will notice that the cord after being much stretched does not at once completely recover itself. Measure and record the length after the weights have been taken out of the pan, and do so again after leaving it slack for a day or two, to find whether, *with time*, the cord completely recovers itself. Remember to hang on the empty pan again when you do this.

## THE LAW OF THE SIMPLE PENDULUM.

**Definition.**—A *simple* pendulum is one formed of a heavy particle attached to a weightless thread, such as is nearly realised by a bullet or small heavy weight fastened to the end of a piece of fine string or cotton. By the *length* of such a pendulum is meant the length from the point of suspension to the centre of gravity of the "bob," it being always understood that the bob used has dimensions which are small compared with the length of the pendulum.

We have seen (Experiments 11 and 17) that, provided the oscillations of such a pendulum are not very large, they are isochronous, *i.e.* of equal duration, whether the amplitude of swing be great or small, provided that it is never very great.

EXPERIMENT 19.—*To show that the time of oscillation is independent of the weight of the bob.*

*Instructions.*—To do this make a pendulum of a piece of thread, with a small weight at the end, *e.g.* one of your metal cylinders, of which you know the position of the centre of gravity; measure the length carefully and record it; then observe the time of a large number (say sixty) of oscillations of small amplitude.

Now substitute a much heavier bob, and having arranged that the length, from point of suspension to centre of gravity, shall be exactly the same as before, again observe the duration of the same number of small oscillations.

*N.B.*—The pendulum should not be wound round a rod because of the error indicated in the accompanying figure (Fig. 97). It may very conveniently be hung from a pair of pliers held by a clip as in Fig. 98.

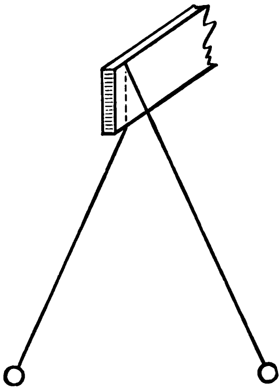

Fig. 97.
BAD SUSPENSION, because the length of the pendulum alters with its position.

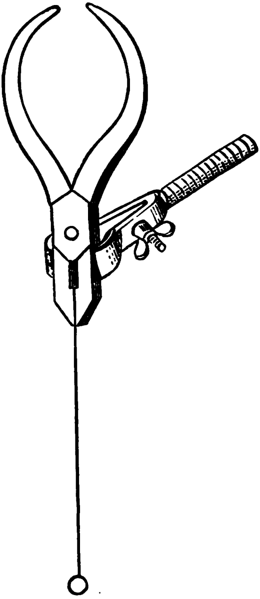

Fig. 98.
GOOD SUSPENSION.

It might be expected that the heavier bob would return more quickly to its position of rest when displaced than the lighter, since the force of recovery is obviously greater. The reason that it does not is that, precisely in proportion as the bob is heavier, so also is it more difficult to move. The greater force acting upon the greater mass generates the same velocity in the same time as the smaller force acting on the smaller mass.

EXPERIMENT 20.—*To find the connection between the length of a pendulum and its time of oscillation.*

*Instructions.*—Make a pendulum of a bullet and a thread, and observe and record the time of a large number (say 100) of half oscillations, (1) with the pendulum 25 cm. long, then with it 50 cm. long, 100 cm. long, 150 cm. long, and finally, 2 metres long, or as much longer as you can make it.

Record as below—

| Length of Pendulum. | Time of 100 half oscillations. | Time of one half oscillation. | $\sqrt{\text{Length}}$. | $\frac{\text{Time.}}{\sqrt{\text{Length.}}}$ |
|---|---|---|---|---|
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

It will be at once apparent (1) that the time of swing does not alter so rapidly as the length. For instance, on doubling the length, the time of oscillation is not nearly doubled. But if you take the square root of the length, and divide the time by it, you will get a constant result, as the last column should show. Now the value of the fraction $\frac{\text{time}}{\sqrt{\text{length}}}$ can only remain the same under all circumstances, provided that when the denominator alters, the numerator is altered in the same proportion. Hence we see that *the time of oscillation is proportional to the square root of the length of the pendulum*, so that, by increasing the length till the square root of it is doubled, the time of oscillation becomes doubled, and so on.

### EXAMPLES.

**Example 1.**—A simple pendulum, whose length is 4 units, makes an oscillation in ·3 second. Find the length of a pendulum which will make an oscillation in 1·8 seconds.

Here the time is increased in the ratio of ·3 to 1·8
or of 1 to 6

∴ $\sqrt{\text{length}}$ „ „ „ 1 to 6
∴ length „ „ „ $1^2$ to $6^2$
or of 1 to 36

$$\therefore \text{Length required} = \text{original length} \times \frac{36}{1}$$

$$= 4 \text{ units} \times \frac{36}{1}$$

$$= 144 \text{ units.}$$

**Example 2.**—A simple pendulum, whose length is 6 units, makes an oscillation in 5 seconds. What will be the time of oscillation of a pendulum ·54 units in length?

Here the length is diminished in the ratio of 6 to ·54
or 1 to ·09

∴ the time is diminished in the ratio of $\sqrt{1}$ to $\sqrt{\cdot 09}$
*i.e.* of 1 to ·3

$$\therefore \text{Time required} = 5 \text{ seconds} \times \frac{\cdot 3}{1} = 1\cdot 5 \text{ seconds.}$$

**Example 3.**—Supposing that (as is nearly the case) a pendulum 1 metre long makes a complete oscillation in 2 seconds, how long must a pendulum be to oscillate once a minute?

Here the time of oscillation is increased 30 times,

∴ the square root of the length must be increased 30 times,

∴ the length must be increased $30^2 = 900$ times,

∴ length required = 900 metres (nearly).

# PART VI.

# HEAT.

(42 *Experiments.*)

## (1) CONDUCTION; USE OF THE THERMOMETER; RADIATION; FUSION AND SOLIDIFICATION.

(18 *Experiments.*)

# PART VI.

# HEAT.

## (I) CONDUCTION.

[THE record of the following experiments should consist of an account in the pupil's own words of what was done and observed.]

### EXPERIMENT 1.—*Preliminary experiment.*

*Instructions.*—The match with which you light the gas does not become hot at the end where you hold it, because wood is a bad conductor. But if you take a stout piece of wire, preferably copper, of the same length, and hold one end in the top part of the gas flame where it just will not melt, the other end soon becomes too hot to hold. Heat is in this case conducted by the copper from the hot to the cold part. But, as you probably know by experience, the end remote from the flame will never become as hot as that in it.

### EXPERIMENT 2.—*On the stationary condition.*

*Instructions.*—Since, however, the remote end of the thick wire gets too hot to touch, and therefore to experiment with take a longer piece of wire, about 20 cm. long (size will do), and heat one end as before; the other end gets hotter and hotter, but finally reaches a stationary stage. If you feel with your finger along the wire, you find that, as you get nearer the flame, the temperature rises, but that for all parts of the wire a stationary stage has been reached. Now, if the temperature of a body or any part of a body is stationary, that body or part of it must lose heat as fast as it gains it.

Every part of the wire is losing heat in three ways:—

1. By conduction to the cooler part next to it.
2. By radiation.
3. By contact with the cooler air.

EXPERIMENT 3.—*To convince yourself of the loss by radiation.*

*Instructions.*—You have only to take the wire out of the flame, and hold the palm of your hand below it, and close to it, to feel the heat radiated.

EXPERIMENT 4.—*To convince yourself of the loss of heat to the air.*

*Instructions.*—Hold the palm of your hand above it, and you will receive, in addition to the heat radiated, that brought by the ascending current of air that has become warmed by contact with it; it will seem hotter.

It is evident, therefore, that every part of the wire is losing heat, and therefore, since its temperature does not fall, it must be receiving heat by conduction from the hot parts next to it towards the flame, and similarly it must lose heat to the cold part next to it away from the flame. So that we see that the heat of the flame is still being conducted away by the wire, though the temperature of the wire does not alter.

EXPERIMENT 5.—*To compare the conductivity of copper with that of iron.*

*Instructions.*—Take a similar wire of each metal, say size No. 21, and about 10 or 15 cm. long; hold the end of each together in the flame, one in each hand, not in the hottest part, where the copper would melt, but near the top; you will find that the remote end of the copper gets hot by conduction soonest, also that when the stationary stage is reached for each the copper is much hotter than the iron in corresponding parts. But the hotter a thing is the quicker does it lose its heat by radiation (see page 163), therefore the cool end of the copper is losing heat quicker than the still cooler end of the iron, and consequently (since its temperature remains fixed) it must be gaining heat by conduction from the flame at a greater rate, *i.e.* the copper lets heat flow through it more quickly than the iron, or is a better conductor.

You see that we judge of the conductivity by the rate at which the heat flows through the metal when the stationary stage has been reached. To say that the copper conducts better because it got hot soonest would not be necessarily quite correct, for the copper *might* be a substance which, *compared with iron*, required but little heat to raise its temperature very much; as a matter of fact, however, it is not so, and it is generally safe to say that if two equal bars of metal have their ends heated to the same temperature, that whose other end gets hot soonest is the better conductor.

## USE OF THE THERMOMETER.

It will first be well to test the correctness of the freezing-point and of the boiling-point.

Experiment 6.—*To test the freezing-point.*

*Instructions.*—Mix some fragments of ice (which may easily be split off a large block by means of a sharp-pointed tool, *e.g.* the handle end of a file) with a little water in a beaker; stir well with the thermometer, and record the lowest point reached, waiting patiently till you are sure it is the lowest, and taking care that the thermometer is well immersed.

Experiment 7.—*To test the boiling-point.*

*Instructions.*—Fit up a flask as in the figure (Fig. 99), taking care that the thermometer does not touch the surface of the water. After the water has boiled for some time, the thermometer will probably not rise so high as the point marked 100°, because a considerable portion of the mercury thread is exposed to the temperature of the air rather than that of the steam. Record the highest point to which the mercury rises.

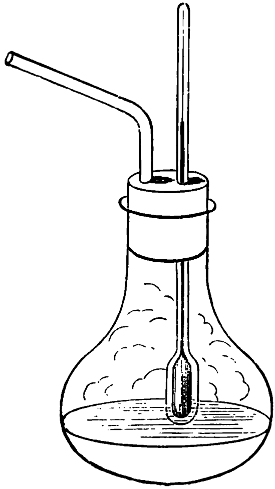

Fig. 99.

EXPERIMENT 8.—*On the boiling-point* (*continued*).

*ructions.*—Then, having pushed the thermometer quite into the water, continue to boil, and observe and record again the highest point that is reached. You may possibly observe that as the water boils away its temperature rises slightly. This is because the water is impure; the salts of lime which it contains remain behind, and form a stronger and stronger solution, of which the boiling-point keeps rising. The increasing proportion of impurities may also be seen by the water becoming visibly discoloured.

EXPERIMENT 9.—*To test the accuracy of the divisions.*

*Instructions.*—This may be done by detaching a column of the mercury by holding the thermometer wrong way up, and giving it a slight jerk. The column should be, say 20 divisions long; now let it slide down the tube, and *record* the position of *each end* in three or four different positions. Then find out, by subtracting the reading of one end from that of the other, the number of divisions of the tube occupied by it in different parts of the tube. Where the tube is wide, the column is shorter, where narrow, longer. In this way you may find out roughly whether your thermometer is trustworthy. For very accurate measures the amount of unevenness of the bore would have to be ascertained and taken into account.

EXPERIMENT 10.—*On the importance of stirring.*

*Instructions.*—It is evident that where we take the temperature of a liquid, we must keep it well stirred, for otherwise the hot liquid will collect at the top. To convince yourself of the importance of this, boil a little water in a beaker, and pour it very gently into some cold water in a second beaker, or, better still, on to a piece of paper or a cork floating on the cold water, in order to break the fall of the water that is poured in. Then observe the temperature indicated by the thermometer, firstly, when plunged deeply into the vessel; secondly, when the bulb is only just immersed: then stir and observe again. Also it is important to have as much of the stem immersed in the liquid as possible, so that as little as possible of the mercury may stand outside. 12

### Experiment 11.—*Estimation of temperature.*

*Instructions.*—It is often useful to be able to estimate temperatures tolerably accurately by touch. Notice, therefore, and record the sensation that water of 20°, 40°, 60° C. produces when the hand is dipped into it.

### Experiment 12.—*Temperature of the human body.*

*Instructions.*—Observe also the temperature of your body by holding the thermometer for some time in your mouth.

## RADIATION.

THE rate at which the temperature of a hot body falls through radiation depends on—

1. The difference between its temperature and that of the surrounding bodies.
2. On the extent of its surface.
3. On the nature of its surface.

The simplest case to consider is that in which the surrounding bodies are all at the same temperature, which may then be called the temperature of the enclosure.

The way in which the rate of cooling depends on the difference between the temperature of the body and that of the enclosure is this:—

A body that is much hotter than the enclosure which surrounds it, *e.g.* a red-hot poker in an ordinary room, cools very fast; but as its temperature is lowered, and approaches the temperature of the surrounding room, it cools more and more slowly, until at last there is no difference between its temperature and that of the surrounding room, and then it does not cool at all.

**Newton's Law.**—Newton discovered that when the difference of temperature between the hot body and the surrounding space is not very great, *the rate of cooling is proportional to the difference between the temperature of its surface and that of the enclosure,* which means, for instance, that if an object is at its surface 10 degrees hotter than the room round it, and falls ·2 degrees in a minute, then it would fall ·1 degree in a minute if it were only 5 degrees hotter, and ·05 degrees in a minute if only 2·5 degrees hotter, and so on.

### EXPERIMENT 13.—*On Newton's Law of Cooling.*

*Instructions.*—In order to test the truth of this, we must take some hot body, and let it cool, and observe the fall of temperature per minute, when its excess of temperature above that of the surrounding air has different values. The thermometer itself is a very good object to choose as the body to be heated and allowed to cool, but it would not do to let it cool in the open air on account of the liability to variable draughts, and it is necessary to know what the temperature of the enclosure is. A good way, therefore, to make the experiment, is to bore a hole in a flat wooden block to admit a perforated cork, through which the thermometer can be stuck into the middle of your tin vessel, as in Fig. 100. The thermometer can be warmed *carefully* in the stream of hot air above the flame of the burner to about 70 or 80 degrees, and then plunged into the enclosure.

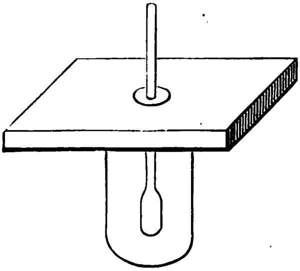

FIG. 100.

In order to keep the temperature of the enclosing tin vessel constant, it should be surrounded by cold water, which may be done by floating it in a large beaker, as in Fig. 101, which is a sectional diagram. The tin, being a good conductor, will always pass on the heat yielded by the thermometer as it *cools to the* water, but the water has such a high specific heat, and there is so much of it, that its temperature will not be appreciably raised thereby. The beaker should be filled with so much water that, when the tin vessel is forced down level with its edge, the water rises to within 2 cm. of the top. It is an advantage to weight the vessel with shot strewn evenly over the bottom. The temperature of the water must first be taken (this gives the temperature of the enclosure), then the thermometer, carefully wiped and warmed as described, is thrust through the cork and block to the right depth, and the whole put on as a lid to the vessel and the beaker together. You must not stick the thermometer through the lid first, and then heat it, for the lid would itself get *warm, and this would* spoil the experiment. The

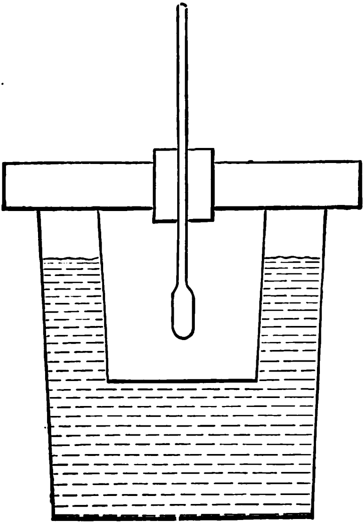

FIG. 101.

thermometer will at once begin to cool rapidly. Wait, watch in hand, till the second-hand is at some notable place on the dial, *e.g.* at the 10th, 15th, 30th, or 60th second, and then glance up at the thermometer, and record the temperature; then in half a minute record it again; and so on till the temperature is within 6 or 8 degrees of that of the surrounding water, taking care in each case to estimate the tenths of a degree. You will now have a list of perhaps a dozen temperatures; by subtracting from each the temperature of the water, you have a list which tells you the excess at each half minute of the temperature of the hot body over the enclosure. Arrange these in a second vertical column, as in the example on the opposite page. The excess is greater at the beginning than at the end, and the *average* excess during each half minute may be taken as the average between the excess at the beginning and the excess at the end. Calculate thus the average excess for the first half minute, then for the second, and so on, and arrange the results in a third vertical column, headed *average excess.* Now, in a fourth column, write the fall of temperature during each half minute in question. You will at once see that, as the thermometer gets nearer and nearer to the temperature of the enclosure, so does the fall in each half minute become less. If the excess and the fall diminish in exactly the same proportion, then the one divided by the other will always have the same value, for if, when the numerator of a fraction becomes two, three, four times smaller, the denominator does so also, then the value of the fraction will not alter. To test this, divide the excess by the fall (one place of decimals will be enough), and arrange the results in a fifth column, headed $\frac{\text{average excess}}{\text{fall}}$. If the numbers in this column are nearly the same, it will show that the fall in a given time is proportional to the average excess during that time, which is Newton's Law.

The following table is an example of an experiment done in the way described.

The temperature of the water was 14°·5.

The first column contains the observed temperature of the thermometer.

The second, the observed temperature of the thermometer *minus* 14°·5, *i.e.* the excess.

The third, the mean between the excess at the beginning of each half minute and that at the end, *i.e.* the average excess.

The fourth contains the fall for the corresponding half minute; and the fifth explains itself.

TEMPERATURE OF ENCLOSURE 14°·5.

| Temperatures. | Excess. | Average Excess. | Fall in degree per ½ minute. | $\frac{\text{Average Excess}}{\text{Fall}}$. |
|---|---|---|---|---|
| 66·5 | 52 | | | |
| 57·5 | 43 | 47·5 | 9 | 5·28 |
| 51 | 36·5 | 39·75 | 6·5 | 6·1 |
| 45·4 | 30·9 | 34·2 | 5·6 | 6·11 |
| 41 | 26·5 | 28·7 | 4·4 | 6·52 |
| 37 | 22·5 | 24·5 | 4 | 6·1 |
| 34 | 20·5 | 21 | 3 | 7 |
| 31·5 | 17 | 18·25 | 2·5 | 7·3 |
| 29·3 | 14·8 | 15·9 | 2·2 | 7·2 |
| 27·5 | 13 | 13·9 | 1·8 | 7·7 |
| 25·9 | 11·4 | 12·2 | 1·6 | 7·6 |
| 24·5 | 10 | 10·2 | 1·4 | 7·6 |

*Interpretation of the results.*—The numbers in the last column are (1) rather irregular, which shows that the fall has been rather irregular. (2) They show, on the whole, an increase in value, which means that the denominator of the fraction has diminished quicker than the numerator, or that the fall is not quite proportional to the excess. (3) The numbers do not vary much, which shows that the cooling has taken place nearly according to Newton's Law.

EXPERIMENT 14.—*To prove that the amount of heat lost by radiation and contact with the air depends on the amount of surface exposed.*

*Instructions.*—Take two equal pieces of tinfoil, about 10 cm. by 5 cm. Squeeze one into a little pellet with small surface exposed. Roll the other quite loosely. Heat both together in a wide dry test-tube over a gas flame, taking care not to melt the tinfoil. Turn out rapidly on to the table. The sheet will cool in a moment, while the pellet will retain its heat much longer.

EXPERIMENT 15.—*To prove that the ability to radiate varies with the nature of the surface.*

*Instructions.*—Select two equal 2-oz. flasks; dry the inside of one with your handkerchief if necessary, and then smoke it thickly outside in the flame of a candle as far as the neck. Coat the other with tinfoil up to the same place. Fill each with hot water to the same height, *i.e.* to the beginning of the neck. Take the temperature of each. Cork them up; set em aside at the back of the table, where there is no draught the temperature of the water in each after twenty or so, and state what the results prove.

EXPERIMENT 16.—*To prove that the ability to reflect heat varies with the nature of the surface on which it falls.*

*Instructions.*—Smoke the inside of a beaker thickly. Let it cool completely. (The cooling may be hastened by pouring cold water round the outside.)

Heat the thermometer very carefully to 80° or 90°, taking care not to burst it by heating it beyond 100°.

Use the perforated block as a lid. Let the thermometer cool inside the beaker. Observe the time required to cool from say 70° to 40°.

Repeat the experiment with the same or a similar beaker lined with tinfoil instead of being smoked, the lid being also lined.

State what the results prove.

## FUSION AND SOLIDIFICATION.

**Observation of the Melting-point.**—In many substances the passage from the solid to the liquid state is gradual, the solid becoming viscous before complete liquefaction; hence the melting-point is often difficult to determine with accuracy.

EXPERIMENT 17.—*To find the melting-point of paraffin.*

*Instructions.*—Cut up a paraffin candle into small pieces, and melt them in a wide test-tube till you have some 30 or 40 cub. cm. of liquid. Then draw out a thin glass tube, about 5 mm. in diameter, into a fine thread, as in Fig. 102. Into this draw up by suction some of the melted paraffin. Then close the point by fusing the extremity in the flame. You have thus secured a fine thread of paraffin within walls so thin as readily to allow heat to pass in or out. Now set a small beaker of water over the Bunsen flame, and stir it with the thermometer, holding the little tube by the side of the bulb, as in Fig. 103. When the temperature approaches the *melting-point,* the paraffin, which, while solid, appears as a

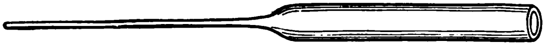

FIG. 102.

white thread in the water, will begin to lose its opacity, and when melted will be quite transparent. The temperature, as shown by the thermometer, at which it becomes transparent, must be recorded. Then the flame may be removed, and the temperature shown when the liquid solidifies and again becomes opaque may be noticed. The mean between the two may be taken as the melting-point. The difference is due to the fact that, while the temperature is rising, that of the thermometer must always be rather behind, or lower than the temperature of the liquid, while, when it is falling, the thermometer will have a temperature somewhat above that of the liquid.

*N.B.*—If during the process of heating the water, the tube should become covered with air-bubbles which obscure the view, these may be wiped off from time to time with the fingers.

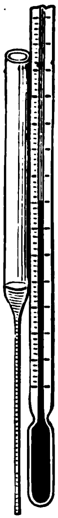

FIG. 103.

EXPERIMENT 18.—*Observation of solidification.*

*Instructions.*—Melt over the flame the paraffin which you placed in a test-tube for the last experiment, watch it cool, stirring it with the thermometer, and record the temperature every half minute. (*N.B.*—You must take care that the liquid is not so hot, when you plunge the thermometer in, as to burst it.) You will find that the liquid at first cools rapidly, but that, as the point of solidification is approached, the cooling is much slower, and that after the outward portions have solidified, the thermometer registers for a long time an *absolutely constant* temperature, which will be very nearly that which you have found as the melting-point. This temperature is, in fact, the temperature of solidification; and the reason that the substance now cools so very slowly is that the liquid part gives up, as it solidifies, its latent heat to the rest, and thus prevents the temperature from falling. (See Experiments on Latent Heat, p. 184.)

# HEAT—(*Continued.*)

## (2) EXPERIMENTS ON HEAT QUANTITY.

(24 *Experiments.*)

**Definition of the Unit Quantity of Heat.**—We shall take as the unit quantity of heat, in our experiments, the amount required to raise one gram of water one degree Centigrade, or, what is evidently the same thing, the amount which one gram of water gives up in falling one degree Centigrade.

*N.B.*—The unit quantity of heat is often termed a "calorie." It is important to show that this amount is, so far as our observations will show, the same for all parts of the scale, from 0° to 100°, for it might happen, for instance, that it required much more heat to raise a given weight of water from 40° to 50° than from 10° to 20°. We will make some experiments to show that this is not the case.

EXPERIMENT 19.—*To show that the quantity of heat given up by a given weight of water in falling through a certain range of temperature in one part of the thermometric scale is able to raise the same weight of water through the same number of degrees in a different part of the scale.*

*Instructions.*—Take two similar thin glass beakers, each of which has a capacity of at least 400 cub. cm. Place them, empty, in opposite pans of the balance, and counterpoise. Now pour into one some cold water till it is not quite half full, and pour into the other an equal weight of hot water at a temperature of about 60° C., adjusting the quantity with a pipette. Now remove each beaker from the balance pan, and take the temperature, first of the cold water, which, being nearly of the same temperature as the air of the room, will not rapidly alter, and then of the hot, stirring the latter well while you do so. Then, rapidly, before the hot has had time to cool below the temperature you have noticed, pour it all into the cold water, and stir the mixture well with the thermometer, and take its temperature. By subtracting the temperature of the mixture from that of the hot water, to start with, you find the number of degrees through which the hot water has fallen; and by subtracting the original temperature of the cold water from the temperature of the mixture, you find the number of degrees that the cold has risen. If your experiment has been well made, you will find the two numbers nearly, but not quite, equal; the number of degrees through which the cold rises will not be quite as great as the number through which the hot falls. Now, this may be due to one of two reasons: *either* the cold water takes more heat to raise it through each degree than the hot, *or* all the heat lost by the hot water has not gone into the cold water. Now it is evident that this latter is really the case, for some of the heat of the hot water has gone to heat the glass in which the cold water was held.

EXPERIMENT 20.—*To test whether the heat lost in this ay is enough to account for the discrepancy.*

*Instructions.*—Make the experiment in a different way, by pouring the cold water into the hot. *Now* the cold water will get heat, not only from the hot water, but also from the hot glass which contains it, so that, if the statement of Experiment 19 is true, we may expect to find the number of degrees through which the cold water rises rather greater than the number through which the hot water falls. If the experiment is well made this will be the case.

The object of using thin beakers and large quantities of water in these experiments is, that the quantity of heat absorbed or lost by the glass may be very small compared with that absorbed or lost by the water it contains.

You will find it difficult to get good results if your hot water is over 60° or 70° C., since it will then cool very fast as it is poured through the air, or while being stirred to take the temperature after mixing, so that you will be unable to ascertain the exact temperatures either before or after mixing.

### EXPERIMENT 21.—*Mixture of unequal quantities of water at different temperatures.*

*Instructions.*—Now vary the last experiment by taking unequal quantities of hot and cold water, say 200 grams of hot and 300 of cold, and observe and record the temperature that results from pouring the cold into the hot. Then calculate what the temperature of the mixture should be, according to the following example:—

**Example.**—"250 grams of cold water at 12° C. were poured into 150 grams of hot water at 54° C. Required the temperature of the mixture, on the supposition that all the heat lost by the hot went to the cold water. Let $\theta$ be the temperature of the mixture which it is required to find. Then, since

$$\left.\begin{array}{c}\text{Number of units of heat lost}\\ \text{by the hot water}\end{array}\right\} = \left\{\begin{array}{c}\text{Number of units of heat gained}\\ \text{by the cold water,}\end{array}\right.$$

$$\begin{aligned} 150\,(54-\theta)^\circ &= 250\,(\theta-12)^\circ, \\ \therefore\ 8100-150\,\theta &= 250\ \ \theta-3000, \\ \therefore\qquad -400\,\theta &= -11100, \\ \therefore\ \theta &= \frac{11100}{400} = 27^\circ{\cdot}75\ \text{C.}" \end{aligned}$$

You can now see for yourselves how much your experiment is in error.

## EXPERIMENTS ON SPECIFIC HEAT.

**Explanation of the terms "Capacity for Heat" and "Specific Heat."**—It is found that it requires more heat to raise a given weight of water through a given range of temperature than to raise the same weight of any other substance through the same number of degrees. This fact may be expressed by saying that water has a greater capacity for heat than any other substance; or again, by saying that the *specific heat* of water is greater than that of any other substance.

*By the* SPECIFIC HEAT *of a substance we mean the quantity of heat required to raise a given weight of it through a given range of temperature, compared with the quantity required to raise the same weight of water through the same range of temperature.* Or again, taking the unit quantity of heat as that quantity which raises one gram of water one degree Centigrade, we may define the Specific Heat of a substance as—

*The number of units of heat required to raise one gram of the substance one degree Centigrade;* or again, *It is the number of units of heat which one gram of the substance gives up in falling one degree Centigrade.*

EXPERIMENT 22.—*To find the specific heat of copper by the method of mixtures.*

*Instructions.*—You are given a small, deep, cylindrical vessel of very thin sheet brass, which requires very little heat to raise *its temperature* through a few degrees. The vessel should be polished outside so as to radiate heat very badly, and placed on a piece of cork, which is a very bad conductor of heat. Place this vessel in one pan of the balance, and counterpoise it. As you will frequently require to counterpoise this vessel in future experiments, make a permanent counterpoise that you can put away and use as required. Now pour into the vessel about 30 or 40 grams of cold water (the quantity should be sufficient to cover the bulb of the thermometer).

Now take 70 or 80 grams of copper wire, cut up into very short pieces, not more than a cm. long; put these into a dry wide test-tube, 3 or more cm. in diameter, and place this in a deep beaker of water, which is kept boiling by a Bunsen flame.[1] Put your thermometer down among the pieces of copper, which can be easily shaken up so as to surround the bulb, and wait till it registers 100°, or remains at a constant temperature a little below 100°.

*N.B.*—In order that the copper may attain so high a temperature, the boiling water must be deep enough to surround the test-tube to a considerable height.

Now take out the thermometer and cool it by a stream of cold water from a tap, and then take, very accurately, the temperature of the cold water in the little vessel (which, since it is used in measuring heat quantities or "calories," is called a "calorimeter"), giving the thermometer plenty of time to acquire the temperature of the cold water. Then pour the copper clippings (whose temperature, having reached the highest point attainable, will not have altered) very rapidl into the cold water, stir well, giving the mixture nearly half inute to arrive at the same temperature throughout; then bserve and record the temperature of the mixture. Now alculate the specific heat of copper in the manner shown in he following example:—

---

[1] *A great* deal of time will be saved if the water is obtained hot *start with* from a large kettle kept constantly boiling.

### *Experiment to find the Specific Heat of Copper.*

70 grams of copper at 99° C. are mixed with 30 grams of water t 13°·5 C. The temperature of the mixture was 28°·5 C.

The water has been raised from 13°·5 C. to 28°·5 C., *i.e.* through 15°, and there are 30 grams of it; therefore it has received $30 \times 15 = 450$ units of heat, and, assuming all the heat lost by the copper to have gone to the water, we see that the copper has lost 450 units of heat,

*i.e.* 70 grams of copper in falling (99 — 28°·5 =) 70°·5 give up 450 units of heat,

∴ 70 grams of copper in falling 1° give up $\frac{450}{70 \cdot 5}$ units of heat,

∴ 1 gram of copper in falling 1° gives up $\frac{450}{70 \cdot 5 \times 70}$ units of heat.
$= \cdot 0912$ units,

∴ to raise 1 gram of copper 1° C. requires ·0912 units, which is therefore the specific heat of copper.

**Correction.**—Now, in this experiment it is evident that all the heat lost by the copper has not gone to the water as we have assumed, but some has gone to heat the vessel, and some to heat the thermometer. We will now find by experiment how many units of heat the vessel requires to raise its temperature 1°. If we find it takes say ($m$) units, then we hall know that it is equivalent to ($m$) grams of water, and hat in our experiment we ought to have reckoned that we ad $30 + m$ grams of water, instead of 30 grams, and thus ave taken the *calorimeter into* account.

EXPERIMENT 23.—*To find the water equivalent of the calorimeter, or little vessel containing the cold water, into which we poured the hot liquid.*

*Instructions.*—Dry the vessel carefully, and counterpoise it. Then take its temperature, which will be that of the air within it. Now take, in a small beaker, some warm water at about 30° C.; stir it well with the thermometer, observing the temperature as you do so, and at once pour some of it into the calorimeter—enough to cover the bulb of the thermometer; stir for a few seconds, and again observe the temperature, which will now be a *little* lower, owing to the calorimeter having chilled the water poured in. *N.B.*—It is well to have the beaker nearly full, so that the water does not get chilled by being poured over its cold side.

Now find and record the weight of the water that has been poured in, and then calculate the "water equivalent" as in the following example :—

*Example of an Experiment made to find the Water Equivalent of a certain Calorimeter.*

Temperature of the calorimeter at first = 10° C.
Temperature of the water before pouring in = 34° C.
" " " after " = 32°·5 C.
Weight of water added = 31 grams.

The water fell through (34 − 32°·5 =) 1°·5, and there are 31 grams of it, therefore it gave up 31 × 1·5 = 46·5 units of heat, and this was sufficient to raise the calorimeter from 10° to 32°·5, *i.e.* through 22°·5 C.

**And since to raise the calorimeter 22°·5 requires 46·5 units of heat,**

**∴ ,, ,, ,, 1° ,,** $\frac{46\cdot5}{22\cdot5}=2\cdot07$ **units**

$=2$ **units very nearly,**

**∴ the calorimeter is equivalent to 2 grams of water.**

The object of using water not hotter than 30° C. is to avoid loss of heat by cooling after it is poured into the calorimeter, and while it is being stirred.

EXPERIMENT 24.—*To find the water equivalent of the thermometer.*

*Instructions.*—Weigh out in the calorimeter enough cold water to cover the bulb of the thermometer when dipped into it. Observe and record its temperature, and place it aside, away from the influence of any flame which would cause its temperature to alter after you have observed it. Now dip the thermometer into boiling water, hold it in it for a few moments till it gets thoroughly hot, then take it out, wipe it very rapidly with a handkerchief, and then hold it just above the water in the calorimeter; of course, by the time you have wiped it and can hold it thus, it will have fallen several degrees below 100°, but if you have been quick, the mercury will still be between 80° and 90°. Watch the mercury descend for a moment till it reaches say 85° or 80°, or some other easily remembered and still high temperature, and immediately lower the thermometer into the water and stir well, and notice, after stirring for *at least* a minute, the temperature of the water. This will now be a little higher than before, owing to the heat *brought to* it by the thermometer, and by *finding the number of* degrees through which the water and calorimeter have been raised, and the number through which the thermometer has fallen, you can calculate the water equivalent of the latter, as in the following example :—

### *Example of an Experiment to find the Water Equivalent of the Thermometer.*

The weight of water taken was 30 grams.
Water equivalent of calorimeter = 2 grams.
Temperature of water before experiment = 16° C.
,, ,, after ,, = 17°·2 C.
Temperature of thermometer before experiment = 85° C.

The thermometer in falling (85 − 17°·2 =) 67°·8 gives up enougl heat to raise 32 grams of water 1°·2, *i.e.* 38·4 units of heat.

And since in falling 67°·8 the thermometer gives up 38·4 units,

$$\therefore \quad ,, \quad 1^\circ \quad ,, \quad ,, \quad ,, \quad \frac{38\cdot4}{67\cdot8} \quad ,,$$

$$= \cdot566 \text{ units of heat}$$

∴ to raise the thermometer 1° requires ·566 units of heat,
∴ the thermometer is equivalent to ·566 grams of water.

EXERCISE 25.—*Now turn back to your experiment on copper, and recalculate the result by adding to the weight of the water used the water equivalents of your calorimeter, and of your thermometer that you have now found.*

EXPERIMENTS 26, 27, 28, 29.—*Find in the same way the specific heat of Iron ; of Zinc ; of Lead* (*shot*) *; and of Mercury.*

*Instructions.*—In the case of iron, very small tacks may be used, and in the case of zinc, finely chopped up sheet zinc The object of having the metal finely divided instead of in a lump, is to enable the water with which it is mixed to have free access to all parts, so that the heat of the metal may be readily imparted to the water. As regards the quantity of each metal that should be used, it is necessary to take care not to use so much that it cannot be easily stirred in the vessel, or so much that the water will not cover it when poured in; and full time must be given to the mixture to acquire a uniform temperature throughout.

# EXPERIMENTS ON LATENT HEAT.

## EXPERIMENT 30.—*Preliminary experiment with ice.*

*Instructions.*—If some ice in small pieces is placed in a beaker of water, and the whole well stirred with the thermometer, it will be observed to sink to the temperature marked 0°. If the beaker be now placed over the Bunsen flame for a short time, so that additional heat is poured into it, you will find that, *if you keep it very well stirred*, the temperature will rise but very little, while when you remove the beaker from the flame, and stir again, the temperature very soon falls again to zero. Now all this time heat has been passing into the mixture both from the flame and from the surrounding air, and yet the temperature of the mixture has not been permanently raised. It is evident that the heat that has entered has been entirely spent in melting the ice and turning it from ice at 0° into water at 0°. The heat thus spent is said to be latent (or *hidden*) in the water, and it is found that not only in the case of ice melting into water, but in all cases of a solid melting into a liquid at the same temperature, heat is similarly absorbed,[1] and by the *Latent Heat* of a liquid is meant—

*The number of units of heat required to convert unit weight of the solid at its melting-point into liquid at the same temperature.*

---

[1] Conversely, the latent heat of a liquid is given up when it solidifies. (See Experiment 18, p. 172.)

Thus the latent heat of water according to the units which we use will be the amount of heat required to melt 1 gram of ice at zero.

EXPERIMENT 31.—*To find the numerical value of the latent heat of water.*

*Instructions.*—Take a thin glass beaker of about 400 cub. cm. capacity, counterpoise it, and then pour in 300 grams of warm water at about 60° C. Remove the vessel from the balance pan, and pour or drop into it, immediately after observing its temperature, some ice that has been previously broken up into small pieces, and stir rapidly till all the ice is melted. The ice should be rapidly dried on blotting-paper or on a cloth as it is put in, so that it carries no water with it. The temperature of the mixture will fall rapidly till all the ice is melted, and care must be taken not to put in more than will melt; if the temperature falls near to zero while much ice is left unmelted, you have put in too much, and must fish out what is unmelted. If, on the other hand, all the ice seems likely to melt before the temperature is within 10° of 0° you may add a little more ice. Notice finally and record the temperature of the mixture when all the ice is melted. Then restore the beaker to the balance, and find out how much ice has been added. Then calculate the latent heat in the manner shown in the following example:—

*Example of the Calculation of the Latent Heat of Water from the results of an Experiment.*

**Weight of water to start with = 200 grams.**
**Temperature ,, ,, = 58° C.**
**Temperature of mixture when all the ice was melted = 8°.**
***Weight of ice added* = 118 grams.**

vessel, expand as they rise, and escape. Since the temperature now becomes stationary, it might be argued that, as before, the extra heat received from the flame is equal to that lost by increased radiation and convection currents in the surrounding air; but it is easy to see that this explanation is insufficient, for if the flame below be made much greater, so that the heat is poured in much more rapidly than before, the water will indeed boil more furiously, but its temperature will be unaltered, so that the loss by radiation and contact with the air must be the same as before. It is evident, therefore, that the water has now some other means of getting rid of the heat poured into it, and that the heat is, in fact, absorbed in the formation of the steam which is given off. Some steam may indeed have been observed rising from the surface of the water before it boiled, but as the surface from which it then escaped was limited in extent, the quantity of heat which could be got rid of in this way was small, and not enough to balance what was poured in from below, so that the water was compelled to rise in temperature. But at last a temperature is reached at which the pressure of the water vapour is so great that it can form bubbles and keep them distended in spite of the atmospheric pressure on the liquid, and these bubbles present additional surface at which evaporation can take place, so that the water has now a new way of getting rid of the heat poured in without being obliged to rise in temperature so as to lose it by more rapid radiation.

The steam which escapes from the water is at the same temperature of 100° C., as may be seen by holding a thermometer just above the surface of water that is boiling rapidly in a flask (see Experiment 7, p. 160), so that the heat spent in evaporating the water becomes latent (or hidden) in the steam, just as the heat spent in melting ice is hidden or stored up in the water produced, and we may define *the Latent Heat of Steam* as

*The number of units of heat required to turn a gram of water at* 100° C. *into steam at* 100° C.; *or, conversely, it is the number of units of heat which a gram of steam at* 100° C. *gives up in condensing into water at* 100° C.

Since it is not so easy to measure the amount of heat which we put into water to turn it into steam as it is to measure the amount of heat which the steam gives up in condensing again into water, we shall adopt the latter method.

EXPERIMENT 33.—*To find the numerical value of the Latent Heat of Steam.*

*Instructions.*—Take a large thin flask (of about 600 cub. cm. capacity) with a wide neck. Counterpoise it empty, and then pour into it from 400 to 500 grams of cold water. Place it on a non-conducting stand, and then lead into it steam from a flask of water that is kept violently boiling, till the temperature is raised, say to 50° C., and then find the weight of steam added.

Certain precautions are necessary. If the steam is led into the cold water by means of an ordinary caoutchouc or glass delivery tube, a considerable quantity will condense on the way, owing to the exposure of the tube to the cold air; and though the water formed by this condensation will trickle down into the cold water in the large flask, yet its latent heat will not be given up to that water, so that the increase in weight of the contents of the large flask will not give the true value of the *amount of steam* condensed there.

To avoid this error, the end of the delivery tube should be fitted with the arrangement shown in the accompanying figure (Fig. 104), in which a narrow tube A, fits inside a wider tube B, which thus serves as a trap to catch the already condensed water that trickles down from the upper tube C. When the condensed water rises nearly to the top of the tube A, the whole may be lifted out of the cold water, and the condensed water poured off, and the experiment then continued again.

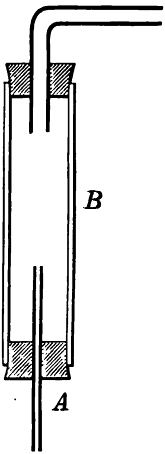

FIG. 104.

Another precaution has reference to the heat lost by radiation during the experiment, as the temperature of the cold water is gradually raised above that of the air. This may be roughly allowed for in the following manner:—Let the time be noticed by a watch when the experiment is begun, *i.e.* when the steam of the boiling water is first led into the cold water, and let the time at which the delivery of the steam is stopped be also noticed, so that the duration of the experiment is known. Then, after observing the temperature of the mixture, let it stand for a minute, stirring it gently with the thermometer, and at the end of the minute observe the loss of temperature by cooling. Let us suppose this to be 1·2 degrees. It is evident that this is not the rate of cooling that has prevailed throughout the experiment, for at the beginning, when the temperature of the water was the same as that of the surrounding air, it did not lose at all by radiation, so that the average rate of cooling during the experiment must be something between 0° per minute and

1°·2 per minute; and we may take it as midway between these two, *i.e.* at $\frac{1\cdot 2}{2} = \cdot 6°$ per minute, so that, supposing the experiment to have lasted for five minutes, we may reckon the loss by cooling at $5 \times \cdot 6° = 3$ degrees, and must add 3 degrees to the temperature of the mixture in order to obtain the temperature to which the cold water would have been raised had there been no loss by radiation. In order to make the loss by cooling as small as possible, the steam should be passed in as quickly as possible, and for this reason the water should be boiled over a large flame.

Another necessary precaution is to screen the cold water from the heat of the flame by which the water in the flask that supplies the steam is kept boiling.

The following is an example of the calculation of an experiment made in the way described :—

### *Experiment to find the Latent Heat of Steam.*

Weight of cold water = 450 grams.

Temperature of cold water = 13°·5 C.

Time of beginning the experiment = 23 minutes 30 seconds.

„ ending „ „ = 29 minutes 30 seconds.

Temperature of mixture (observed) = 48° C.

Fall of temperature in 1 minute at end of experiment = ·5° C.

∴ Average rate of cooling during experiment = ·25° C.

∴ Loss of temperature during the six minutes that the experiment lasted = 6 × 25° = 1°·5 C.

∴ Corrected value of temperature of mixture = 48° + 1°·5 = 49°·5 C.

Weight of steam condensed = 28 grams.

Each gram of steam on condensing gives up its latent heat (L), and becomes a gram of water at 100°.

This water then mixes with the rest, and finally attains the temperature of the mixture 49°·5, thus losing (100 − 49·5) units,

∴ Heat *given up by the steam* on condensing = 28 L units,

and Heat given by steam-water after condensing $= 28\ (100 - 49{\cdot}5)$ units
$= 28 \times 50{\cdot}5$ units
$= 1414$ units,

and the total heat given up has been sufficient to raise 450 grams of water from 13°·5 C. to 49°·5 C., *i.e.* through 36° C.,

$$\therefore 28\ \text{L} + 1414 \text{ units} = 450 \times 36 \text{ units},$$
$$\therefore 28\ \text{L} = (16200 - 1414) \text{ units} = 14786 \text{ units},$$
$$\therefore \text{L} = \frac{14786}{28} = 528{\cdot}07 \text{ units}.$$

The quantity of heat absorbed by the glass has here been left out of account. But the water equivalent of the flask may be found in the manner previously described, and the correction duly applied.

**Specific Heat of other Liquids.**—We will take Turpentine as an example of a liquid which may be stirred up with water, and Alcohol as an example of one which may not.

EXPERIMENT 34.—*Preliminary experiment to show that when turpentine and water are mixed, there is no chemical action resulting in an appreciable absorption or evolution of heat.*

*Instructions.*—Pour into a wide test-tube enough turpentine to cover the bulb of the thermometer, and take its temperature; into this pour about the same volume of water of the same temperature, stir well, and observe that the temperature does not alter.

You will notice that the water, being the denser, sinks to the bottom, hence when we come to mix turpentine and water at different temperatures it will be best to use hot vater and cold turpentine, and to pour the water into the urpentine so that in passing to the bottom through the urpentine the water may be the better able to impart its heat.

The boiling-point of turpentine is much higher than that of water, so that we may pour boiling water into cold turpentine without causing the latter to boil or lose much heat by rapid evaporation.

EXPERIMENT 35.—*To find the specific heat of turpentine.*

*Instructions.*—Into the thin brass calorimeter, whose water equivalent ($w$) has been found, pour enough turpentine to fill it rather more than half full; find the weight of turpentine, suppose it to be N grams, take its temperature ($t$). Into this pour what you estimate to be about half its weight of boiling water, stir vigorously, and take the temperature (T) when the thermometer gives the same reading, whether immersed so deeply as to reach the water, or only in the turpentine. (You may find that two or three minutes elapse before the temperature can be taken.) Find by weighing the weight (W) of water added. Let $k$ be the water equivalent of the thermometer.

To calculate the result you may proceed as follows :—

Let $x$=the specific heat of turpentine.

Then 1 gram of turpentine takes $x$ units of heat to raise its temperature 1° C.

∴ N grams in rising from $t°$ to T° take N $(T-t)\,x$ units,
and the calorimeter and thermometer in rising through the same range takes $(w+k)\,(T-t)$ units,
and the (W) grams of water in falling from 100° to T° have lost W $(100-T)$ units,

∴ Since heat gained by turpentine and calorimeter and thermometer=heat lost by hot water,

$$N\,(T-t)\,x+(w+k)\,(T-t)=W\,(100-T)$$

$$\therefore x=\frac{W(100-T)-(w+k)\,(T-t)}{N\,(T-t)}.$$

**Sources of Error.**—It is evident that the weakness of this experiment lies in the length of time required for stirring before the temperature of the mixture can be taken, since during this time the mixture is losing its heat to the air and by radiation. This loss may be lessened by wrapping the calorimeter loosely in cotton-wool, and putting it thus enveloped into an empty beaker as a stand, as in the accompanying figure (Fig. 105). The cotton-wool is itself a very bad conductor of heat, and prevents the circulation of cold air round the calorimeter. But even when this precaution is taken, the loss of heat will still be very appreciable in the two or three minutes that may be required for complete mixing, and it is not very easy to measure the loss in any way. Moreover, there is another source of error in the uncertainty which attaches to the value of the water equivalent of the calorimeter and thermometer, and which is more important in this than in previous experiments, because, since turpentine has a much smaller specific heat than water, a larger *proportion* of the heat imparted is absorbed by the calorimeter in the present instance. We may avoid both these sources of error by making an experiment of a somewhat different kind.

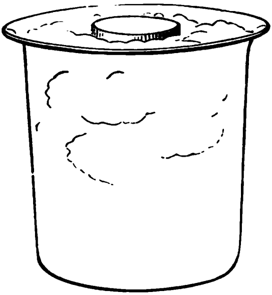
Fig. 105.

**Another Method.**—It is evident that a certain weight of turpentine will have the same capacity for heat as a certain smaller weight of water, and that if we can find *the exact* weight of water which is equivalent to a certain weight of turpentine, then we shall know the proportion in which the specific heat of turpentine is less than that of water. The equivalent quantity of water may be found in the manner described in the following experiment.

EXPERIMENT 36.—*Second experiment to find the specific heat of turpentine.*

*Instructions.*—Counterpoise the calorimeter, and then fill it about three-quarters full of turpentine, and weigh the turpentine, adding or removing a little to make the weight an exact whole number of grams. Then set the calorimeter, with the turpentine in it, in a current of cold water from the tap, while you weigh out as much finely chopped copper wire as you think can be poured quite safely into the calorimeter without causing it to overflow. Then heat the copper to 100°, or as near as you can get it, in the manner described in Experiment 22. Take the temperature of the turpentine, and pour in the copper; stir well for half a minute, and then observe the temperature of the mixture.

Now repeat the experiment in precisely the same way, only using, instead of turpentine, *half* its weight of water. If, after pouring in the same weight of copper at 100°, you find the temperature of the mixture to be the same as in the previous case, you will know that the turpentine is thermally equivalent to half its weight of water. If the temperature of the mixture in the second experiment is lower than in the first, then you will know that you have taken too much cold water; if higher, that you have taken too little. Now repeat, with rather more or rather less water, according to the result, until *you can say that the* equivalent quantity of water lies between ($n_1$) grams and ($n_2$) grams. Let the weight of the turpentine be N grams. Calculate thus—

If the water equivalent of the N grams of turpentine were $n_1$ grams,

Then 1 gram of turpentine would be equivalent to $\frac{n_1}{N}$ grams of water,

∴ The specific heat of turpentine would be $\frac{n_1}{N} =$ .

Again, if $n_2$ were the water equivalent, the specific heat of turpentine would be $\frac{n_2}{N} =$ . . . .

∴ The specific heat of turpentine lies between $\frac{n_1}{N}$ and $\frac{n_2}{N}$.

It is evident that in this experiment it is unnecessary to know how much of the heat yielded by the copper is absorbed by the calorimeter, or how much is lost by radiation during the stirring, since the amount is the same in both cases, and therefore the remaining heat, which is all we are concerned with, is the same.

**Variation of the Experiment.**—Instead of using a metal, which, after all, does not bring over much heat with it, we may still use water, as in Experiment 35, and may make the experiment in a rather different manner.

EXPERIMENT 37.—*Third experiment to find the specific heat of turpentine.*

*Instructions.*—Take a large test-tube (about 20 cm. long by 3 cm. wide), and fit it with an india-rubber cork perforated with a hole, through which a thermometer is passed, fitting air tight. Counterpoise the empty test-tube in a beaker, and then pour in 50 grams of cold water from the tap. Into this pour rapidly 20 grams of water, that have been weighed out in a smaller test-tube, and then heated say to 70°. (*N.B.*—While this is being weighed out and heated, the test-tube of cold water should be placed in a stream of water from the tap to keep its temperature constant.) Cork up, and shake the mixture vigorously for half a minute, then take the temperature T.

The 20 grams of water, in falling from 70° to T, have given up sufficient heat to raise the cold water and the glass to T°, besides what was lost by radiation and to the air during the shaking.

Now repeat the experiment *in exactly the same way in all respects*, only, instead of pouring in 20 grams of water at 70°, pour in 40 grams of turpentine at 70°. If the final temperature of the mixture is the same as before, then you will know that the 40 grams of turpentine are equivalent to 20 of water. If the final temperature is less, then you must try again, taking more turpentine; if the final temperature is greater, then you must take less turpentine, until you find that equivalent amount lies between certain narrow limits.

EXPERIMENT 38.—*Preliminary experiment to find the specific heat of Alcohol (Spirits of Wine).*

*Instructions.*—Mix together some alcohol and water at the same temperature, just as you did turpentine and water in Experiment 34. You will find that in this case heat is evolved, and the mixture becomes warm. This liberation of heat would disturb the experiment if we tried to find the specific heat of alcohol in the same way as we have found that of turpentine, by pouring water into it. Consequently, we must adopt *some other method.* We may mix with it any substance of which we know the specific heat, for example, pieces of some metal or mercury, or turpentine, provided that no liberation of heat takes place owing to chemical action. But since alcohol boils at a low temperature, the metal could not be used very hot, and it is therefore better to choose turpentine, which will bring over more heat with it.

PRELIMINARY EXPERIMENT 39.—*Make the preliminary experiment of mixing about equal quantities of alcohol and turpentine of the same temperature, and observe whether there is any rise or fall of temperature on mixing.*

### EXPERIMENT 40.—*To find the Specific Heat of Alcohol.*

*Instructions.*—This may be done by mixing with turpentine in various ways. Since the two liquids are of nearly the same density, they mix much more readily with each other than does water with turpentine, and consequently the error due to cooling, while the mixture is being stirred, is unimportant.

Make the experiment of pouring some boiling alcohol from a test-tube into say 50 grams of cold turpentine contained in the calorimeter, and calculate the result as in the following example.

*Experiment to determine the Specific Heat of Alcohol (Methylated Spirits) by mixing with Turpentine.*

The boiling-point of the alcohol =79°. The alcohol was poured boiling into the cold turpentine.

Weight of turpentine =50 grams.
Temperature of turpentine =13° C.
Temperature of mixture =27°·5 C.
Weight of alcohol =10·2 grams.
Specific heat of the turpentine used =·47

**Water equivalent of calorimeter and thermometer together $= 2·6$ grams.**

**Let $x =$ the specific heat required.**

**Then 1 gram of alcohol in falling 1° gives up $x$ units of heat, therefore 10·2 grams in falling $(79 - 27°·5)$ give up $x \times 10·2\ (79 - 27·5)$ units, and thus is able to raise the temperature of the calorimeter and thermometer from 13° to 27°·5, *i.e.* through 14°·5, and the heat absorbed by the two latter together $= 2·6 \times 14·5$ units, and that absorbed by the 50 grams of turpentine $= 50 \times ·47 \times 14·5$ units.**

**Therefore, since—**

$$\begin{aligned} \text{Heat lost by alcohol} &= \text{heat gained by turpentine, calorimeter, etc.} \\ x \times 10·2\ (79 - 27·5) &= 2·6 \times 14·5 + 50 \times ·47 \times 14·5 \\ \therefore x &= \frac{378·45}{525·3} \\ &= ·720. \end{aligned}$$

EXPERIMENT 41.—*Now devise an experiment on the model of Experiment* 37 (*supra*), *to find the amount of alcohol that is thermally equivalent to a certain weight of turpentine.*

EXPERIMENT 42.—*To find the latent heat of alcohol vapour at its boiling-point.*

*Instructions.*—This should be made precisely in the same way as the experiment to find the latent heat of steam, the vapour of the boiling alcohol being condensed in cold alcohol instead of cold water.

*N.B.*—It is necessary when alcohol is boiling over a flame to take precautions against its taking fire should the glass break. The flask containing the hot alcohol may be held inside a large beaker of water, that is kept boiling over a flame.

The following is an example of the calculation of an experiment made in this way.

### *Experiment to find the Latent Heat of Vaporisation of Methylated Spirits of Wine.*

| | |
|---|---|
| Weight of cold methylated spirits | =500 grams. |
| Temperature ,, ,, | =9° C. |
| Temperature of mixture | =23°. |
| Weight of vapour condensed | =17 grams. |
| Boiling-point of the methylated spirits | =79°. |

The duration of the experiment was five minutes, but the rate of cooling at the end was so small that the correction for it was neglected.

The specific heat of the methylated spirits had been found by previous experiments to be ·7.

Let L stand for the latent heat of vaporisation required.

Then the heat given up by 17 grams of vapour in condensing and then falling from 79° to 23° = heat absorbed by 500 grams of alcohol in rising from 9° to 23°.

$$\begin{aligned} 17\,L + 17\,(79-23)\times{\cdot}7 &= 500\,(23-9)\times{\cdot}7 \\ 17\,L + 666{\cdot}4 &= 4900 \\ \therefore L &= \frac{4900-666{\cdot}4}{17} \\ &= \frac{4233{\cdot}6}{17} \\ &= 249{\cdot}0. \end{aligned}$$

The flask used in this experiment had been found by a previous experiment to be equivalent to 16 grams of water. If we take this into account, the calculation becomes—

$$\begin{aligned} 17\,L + 17\,(79-23)\times{\cdot}7 &= 500\times(23-9)\times{\cdot}7 + 16\,(23-9) \\ 17\,L + 666{\cdot}4 &= 4900 + 224 \\ \therefore L &= \frac{5124-666{\cdot}4}{17} \\ &= \frac{4457{\cdot}6}{17} \\ &= 261{\cdot}6. \end{aligned}$$

This number lies between the values 208 and 264, which are the latent heats of vaporisation of ethyl alcohol and methyl alcohol respectively, and of which liquids the methylated spirit is a mixture, *with some* water, which latter constituent tends to raise the latent *heat considerably.*

# PART VII.

# MAGNETISM.

(55 *Experiments.*)

# PART VII.

# MAGNETISM.

[The Student should record in his own words the *object* of each experiment (where this can be stated); the *manner* in which he makes it; the *result observed;* and the *conclusions drawn.*]

The magnets with which we are most familiar are bars of steel, either straight, or bent into the form of a horse-shoe. Let us take a straight bar magnet, and find out by experiments, carefully made and recorded, what are the properties by which it differs from a similar unmagnetised bar of steel.

Experiment 1.—In the first place, we find that it wi attract pieces of iron towards its end; thus, if we present on end of the magnet to a small nail or tack, the latter will, i the magnet be a strong one, leap up and then adhere to it.

It appears that the magnet exerts a pull on the nail across the air which separates them.

Experiment 2.—If we wrap a thin piece of paper round the end of the magnet, we find that the tack is still attracted, showing that the force is exerted either through or round the paper.

EXPERIMENT 3.—If we wrap up the whole of the magnet, we find no diminution of the action, proving that the action is exerted *through* the paper.

It does not follow from this that the magnetic force is exerted through any other substance, but we shall find later on that it is exerted through a great variety of substances.

EXPERIMENT 4.—If we repeat these experiments with the other end of the bar we obtain the same results.

EXPERIMENT 5.—If we now plunge the end of the magnet into a heap of small nails or tacks, we find that when one is adhering to the end of the magnet, another will adhere to that, and so on, as if the power to attract iron was transmitted from the magnet to the nail in contact with it, and from that to the next, and so on.

But it is evident that the power diminishes as the number and length of the chain of nails is increased.

EXPERIMENT 6.—If instead of tacks we use still smaller fragments of iron, viz. iron filings, and plunge the end of the magnet into them, we shall find that they adhere to it in a curious tuft. Make a diagram of the tuft.

*N.B.*—The box of iron filings should never be used without a sheet of paper under it to prevent spilling the filings on the table.

EXPERIMENT 7.—If we now plunge the other end into the filings, we shall obtain a similar tuft, and it is worthy of notice *that if* we make the experiment carefully, the two tufts will be alike both in size and shape, indicating roughly that the power of the magnet to attract iron is equal at the two ends.

EXPERIMENT 8.—If we lay the magnet on the middle of a sheet of paper, and then sprinkle filings all over the magnet, we shall find, on carefully lifting it up, that none adhere to the middle, but that they accumulate more and more thickly towards the ends. This shows that the magnetic power resides chiefly at the end of the bar, and it is sometimes for convenience supposed to be concentrated at two definite points near the ends; these points are called the poles of the magnet, and the line joining them is called the magnetic axis.

EXPERIMENT 9.—If we now hold the magnet horizontally, we may hang on tacks one below another in vertical rows at different distances from the centre, as in the figure (106), and the length of the chain that will hang at any point may be taken as a rough indication of the power of the magnet at that point, so that we may represent the strength of the magnet at different points by means of a curve such as C D, which is so drawn that the perpendicular distance P P, from any point P of the magnet to the curve represents the length of the chain of tacks which will adhere at this point.

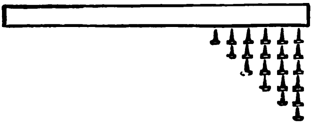

FIG. 106.

Draw *for yourself* (as well as you can) the curve belonging to your own magnet, noticing what makes the experiment difficult and unsatisfactory.

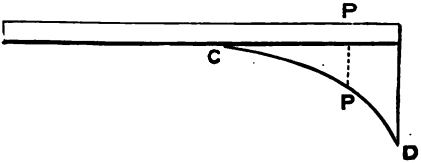

FIG. 107.

EXPERIMENT 10.—When the end of a magnet attracts a nail brought near it, the nail in its turn attracts the end of the magnet. This may be shown by balancing the magnet on an inverted watch-glass, as in the figure (Fig. 108).

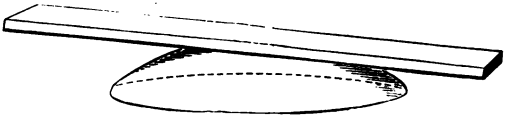

FIG. 108.

EXPERIMENT 11.—Not only does the nail attract the magnet, but it attracts it with precisely the same force with which it is itself attracted.

To prove this, fix a large nail to the side of the balanced magnet after it has come to rest by means of two bits of beeswax. You will find that there is no motion of the system, showing that the attraction of the magnet for the nail tending to pull the system one way round is equal to the attraction of the nail for the magnet tending to pull it the other way round.

**Directive property of a balanced Magnet.**—We will now pass to another most important property of our *steel bar,* of which we may have found some indication whilst making the last experiment, viz. the property of pointing in a particular direction when free to turn about a vertical axis.

There is after all a good deal of friction between the watch glass and the magnet, which prevents the latter from turning as freely as it might, and we will therefore use a more delicate means of balancing it.

EXPERIMENT 12.—A good way is to hang it in a paper stirrup by a single fine cord strong enough to bear its weight, and which does not untwist of itself, such as a piece of horse-hair, catgut, or carefully woven silk fishing-line.

It will now be found, that if we are careful not to let the magnet spin round so as to twist the cord, it always comes to rest in one particular position.

If we twist it round a very little, it will swing back to the old position, beyond it and back again, and so backwards and forwards, the swings or oscillations becoming each time smaller and smaller (of less amplitude), till it comes to rest pointing in the same direction as before. In making the experiments, we must take care to avoid all draughts, which might blow the magnet round. The direction it takes up may be partly affected by our having left some pieces of iron in its neighbourhood, so we must carefully remove from the table all iron when we make the experiment.

EXPERIMENT 13.—It will be observed that at whatever table we make the experiment one end of the magnet always points towards the north, and that if the magnet be moved in the stirrup so that the end which first pointed towards the north is now *towards the south*, it will not remain in this position, but twists round again so as to make the same end point northwards as before.

We thus find that the ends of the magnet, which have so far seemed precisely similar, can really be distinguished by this property of turning northwards or southwards. We will follow the usual custom of *marking* the end which seeks the north: which is conveniently done by gumming a slip of paper round it.

This is much better than making a file-mark, for we shall see later that scratching a magnet seriously weakens it. We shall for the future refer to the end which turns to the north as the "marked" or "north-seeking" end, or sometimes as the N. end, and to the other as the "unmarked" or "south-seeking," or sometimes as the S. end.

You can hardly tell for yourselves whether your magnet points exactly N. or not. But if you were to fix a rod upright in the ground, and mark the direction of its shadow on the ground in the middle of the day, when the sun is at its highest point, or due south, you would then have a due N. and S. line on the ground, and if you were to bring the centre of your magnet over this line, you could observe whether it made any angle with it.

EXPERIMENT 14.—As an exercise of this kind, suppose the N. and S. line to be parallel to the side of your table, and measure the angle between this line and the direction of the magnet.

A convenient way of doing this will be to place a sheet of paper at one corner of the table, with its two edges flush with the sides of the table, and then to hold the suspended *magnet* over it, and, when this is in its position of rest, lower t gently on to the paper, and then mark with a dot on the aper the position of the middle point of each end. The line oining the two dots gives the direction of the magnetic axis, nd the angle between this and the side of the table is shown y drawing a second line parallel to the edge of the paper. he angle should then be measured by a protractor (a divided emicircle), and the paper inserted in the note-book as part of he record.[1]

EXPERIMENT 15.—The experiment of suspending, finding, nd marking the north-seeking end must now be repeated ith the second magnet given you.

Of course the first magnet must be put far away (on the round) while the experiments are made.

## Attraction and Repulsion of Magnetic Poles.

EXPERIMENT 16.—Now hang up one of the magnets in the tirrup, and, having brought it to rest, take the other magnet n your hand, and bring up the marked or N.-seeking end to he marked or N.-seeking end of the suspended magnet. It ill be found that the two ends repel each other.

Now bring the same marked or N.-seeking pole of the nagnet held in your hand to the unmarked or S.-seeking ole of the suspended magnet.

The two will be found to attract each other. Now reverse he magnet in your hand, and present its unmarked or .-seeking end, first to the marked, and then to the unmarked, nd of the suspended magnet. Observe and record the results.

---

[1] This *experiment may* afterwards be performed much more *ccurately with a compass* needle.

If you made the experiment with many magnets, you would always find the same result, and you would thus discover the very important law that

> *Poles of the same name repel each other* (for *marked* repels *marked*, and *unmarked* repels *unmarked*),
>
> while *Poles of unlike names attract each other* (for *marked* attracts *unmarked*, and *unmarked* attracts *marked*).

If a new magnet were given us, we have now a means of finding out which is its N.- and which its S.-seeking end; without absolutely hanging it up and trying. For if we have a magnet already suspended, we have only to present one pole of the new magnet to one pole of the suspended magnet, and the result will tell us at once whether the presented pole is N.- or S.-seeking. The most convenient form of suspended magnet to use for such a purpose is a compass needle, which is simply a small light magnet pivoted at its centre on a vertical axis, and with its N.-seeking end already marked.

A darning-needle with its head stuck in a wooden block serves as a support, while the compass needle may be sheltered from draughts by putting a beaker over it, which can also be so placed as to prevent the needle from swinging too far from its position of rest.

EXPERIMENT 17.—We find at once that a magnet will act through the glass just as if there were none there; and if the hand, or a block of wood or paper, be placed between a magnet and the needle, the action will be in no way impaired. These experiments show the transparency of such substances *to the* magnetic action.

Before making any further experiments with the needle, it is well to assure yourselves that its N.-seeking end is rightly marked.

**How to make Magnets.**—The magnets given you have been made from ordinary bars of steel by rubbing them in a suitable manner against the poles of a very strong magnet, and you may use the magnets you have got for magnetising other pieces of steel.

To make a magnet of a steel knitting-needle.

1*st Method.*—

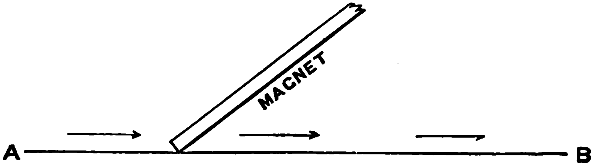

Fig. 109.

Experiment 18.—Lay the knitting-needle on the table, and stroke it several times in the *same direction* with one pole of a bar magnet.

Record which pole you stroke it with.

Then successively present the ends of the needle to one pole of the compass needle, first the end *from* which you drew the magnet and which you touched first, next the end *towards* which you drew it and touched last.

Record the result in each case.

You may now test the equality of the poles of the new magnet by the adherence of filings.

*Draw a diagram showing* how the filings adhere.

EXPERIMENT 19.—*2nd Method.* Stroke a second needle from the centre to the end several times with one pole; then from the centre to the other end an equal number of times with the other pole.

Test the "polarity," as before, by means of the compass needle, and record, with a diagram, distinguishing between the ends stroked by the marked and the unmarked poles of the magnet.

Test the equality of the strength of the poles by iron filings.

**Intermediate Poles.**—If we did not take care to stroke the knitting-needle regularly in the way described, we should obtain what are called "intermediate poles."

EXPERIMENT 20.—Make the experiment of stroking a fresh knitting-needle, first several times from the centre to one end, then several times from the centre to the other end, using all the time, say, the S.-seeking end of the magnet. Now, having laid the needle flat on a piece of white paper, sprinkle filings all over it, and record what you find, giving a diagram.

Now test the magnetisation along the knitting-needle, by holding it vertically, with different parts in succession near to the end of the compass needle.

Show by a diagram the arrangements of poles in the whole length.

**Effect of breaking a Magnet.**—We have not, so far, succeeded in getting a magnet with only one kind of pole. It may appear that, since the middle part of a magnet exhibits no magnetisation, the effect of breaking it in the middle will be to obtain two magnets, each with only one pole.

EXPERIMENT 21.—Make the experiment with one of your regularly magnetised knitting-needles, breaking it by a sharp wrench with a pair of pliers, having previously marked the N.-seeking end by sticking it into a bit of cork.

Now test the freshly broken ends of each piece with the compass needle, and record the result, giving a diagram showing the magnetisation of the broken needle.

Test also with iron filings, and record the result.

It will now occur to you, that, if you could put together the broken pieces again, the two opposite poles would neutralise each other, and would not affect a body outside, and that the reason that the middle of a magnet does not attract iron is not that there is no magnetisation there, but that opposite poles there neutralise each other.

The same reasoning will hold good for the middle of the two new short magnets.

EXPERIMENT 22.—Break each of these again in half; test as before, and record the result.

**Notion of Molecular Magnets.**—Since there does not appear to be any limit, except the size of the molecules of steel, to the number of short magnets into which we might thus break up a long one, physicists have been led to conclude that a magnet may be regarded as made up of an indefinitely large number of small molecular magnets laid pole to pole, as in the diagram (Fig. 110), so that in the middle opposite poles neutralise each other, while at the ends the poles of the molecular magnets are not neutralised.

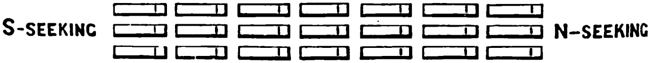

FIG. 110.—Diagram illustrating supposed internal structure of a Magnet.

It is to be observed that we have not yet shown any reason for drawing the molecular magnets longer than they are broad. We shall find later on that there is some reason.

**Different Magnetic Behaviour of Steel and Soft Iron.**—*Remarks on "Hardness."*—Steel is said to be harder than iron because its particles are less easily separated or displaced than those of a piece of iron. Thus a steel file will tear apart the particles of a piece of iron. One kind of iron is harder than another. Steel contains carbon as well as iron. The less the amount of carbon the softer it is. The purest iron is the softest, and is most easily hammered into different shapes.

If you try to magnetise, instead of a steel bar, a bar of soft iron,—for example, a large nail,—you will find that though you stroke it many times in the manner described, it exhibits afterwards little or no magnetic power.

EXPERIMENT 23.—You should test for magnetic power in the nail, after stroking it, first with iron filings, then with the compass needle, presenting each end in turn to each end of the needle. If the needle is always attracted, the nail is not a magnet, but only a piece of soft iron, which always attracts a magnet. If repulsion, under any circumstances, takes place, it is a magnet. *Repulsion of one pole of the needle is the only* SURE *test that the object presented to it is a magnet.*

We must not, however, conclude that because the nail exhibits little or no magnetic power afterwards, that it has not received it while being stroked. Indeed, we will now show that, while the magnet was near, the nail was powerfully influenced, and became itself a magnet, but that it lost its power when the magnet was withdrawn.

Select a piece of soft iron (a nail), about 6 cm. long, that is not already a magnet (or whose magnetic power is very weak).

EXPERIMENT 24.—Hold it vertically, with the point dipping into the box of filings. Now bring one end of the magnet over it, preventing the two, however, from touching (which may be done by inserting between them a bit of paper). On lifting the two, filings will be found to adhere to the nail. Remove the magnet, and they drop off.

This proves that the end of the nail remote from the magnet becomes a magnetic pole for the time being. We will now make the experiment so as to show that the end of the nail nearest the magnet also becomes a pole.

EXPERIMENT 25.—Hold the magnet against the edge of the open box of filings, and plunge the nail into the filings at

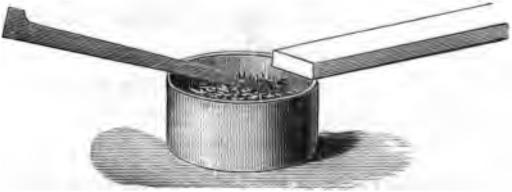

FIG. 111.

that side, as in the figure (Fig. 111). On raising the nail.

filings will be seen to adhere. Remove the magnet, and they drop off.

**Definition of "Induction."**—The action of the magnet on the nail in these two experiments goes by the name of "magnetic induction." The magnet is said to induce magnetism in the nail.

The pole of the magnet influencing the nail is called the *inducing* pole.

### Steel not so easily influenced by Induction as Soft Iron.

EXPERIMENT 26.—Repeat the last two experiments with an unmagnetised piece of steel,—a knitting-needle of about the same length as the nail. Observe and record the results.

**Definition of "Coercive" or "Retentive" Force.**—The fact that steel is less easily influenced by a magnet than iron, while, on the other hand, it retains its magnetism much longer, is sometimes expressed by saying that steel has a much greater "coercive force" than iron. A better phrase is "*retentive power.*"

**To find the Nature of the Induced Poles.**—The adhesion of filings to the nail when the magnet was near only told us that its ends became magnetic poles, but did not tell us whether N.- or S.-seeking. We will now make an experiment to find out.

EXPERIMENT 27.—Present the N.-seeking pole of the magnet to the N.-seeking pole of the needle in such a manner that the latter is driven against the covering glass, so as to be prevented from turning round (see Fig. 113, which is the "plan" of Fig. 112), but let the force between the two poles act very nearly in the direction of the length of the needle. Then bring up a nail, holding it close to, but not touching, the pole of the magnet, and so as to be a prolongation of the magnet (see Figs. 112, 113), and observe the action between the end of the nail and the N. pole of the needle. State what the experiment proves.

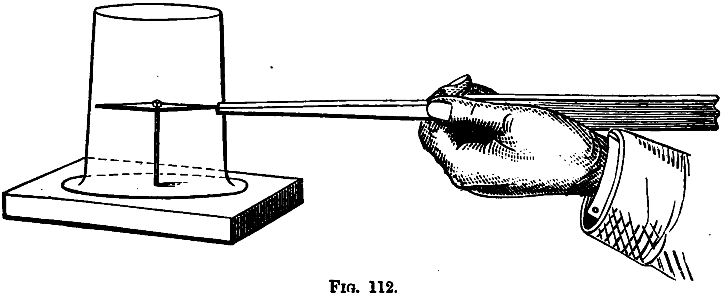

FIG. 112.

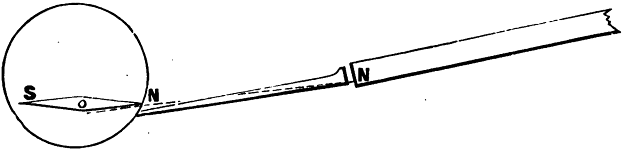

FIG. 113.—PLAN.

EXPERIMENT 28.—Now do the same to the other end of the needle. Again record the result, and state what it proves.

EXPERIMENT 29.—Now repeat the experiment, using, however, the other end of the magnet. Record and explain as before.

By these experiments we learn that the pole induced in the remote end of the nail is of the same kind as the inducing pole.

We will now prove that the pole induced in the end near the magnet is of the opposite kind to the inducing pole.

EXPERIMENT 30.—Remove the covering glass from the needle. Hold the magnet horizontally with one pole, say the N., opposite the S. pole of the compass needle, and close to it. Now hold the nail horizontally, as in the figure (Fig. 114), and move it up as in the figure, as if to poke the end of the needle close to the magnet. The needle will be observed to be repelled when the nail is quite close. This proves that the end of the nail is a pole of the same kind as that of the needle, and of the opposite kind to that of the magnet.

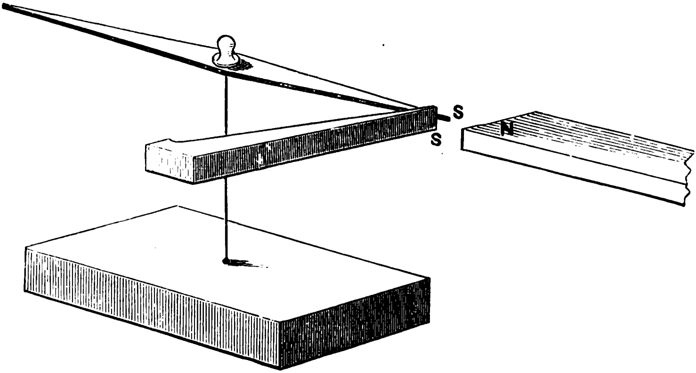

FIG. 114.

**Law of Induction.**—Hence we see that when a magnetic pole is placed near a piece of iron, *an opposite pole is induced on the near side, and a similar pole* on the far side, as illustrated by the diagram.

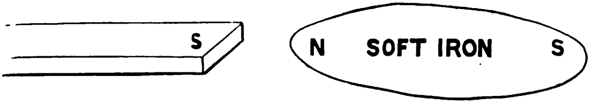

Fig. 115.

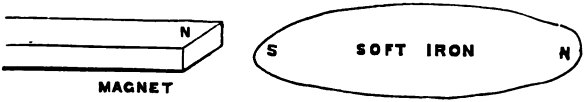

Fig. 116.

This explains the adhesion of the chain of successive nails to a magnet.

It also explains the fact that if two chains of nails be hung side by side from the same magnetic pole, the lower ends repel each other, as is seen by the fact that we cannot by swinging the magnet about bring them together.

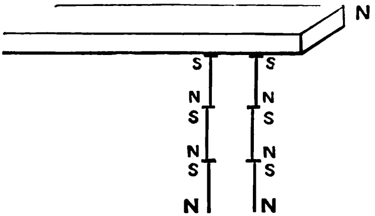

Fig. 117.

Experiment 31.—Now try to contrive an experiment by which two pieces of iron shall be made to repel each other without either being touched by a magnet or by any other piece of iron.

Experiment 32.—The following experiment is an interesting one. Hang as many nails as you can from the pole of a magnet. Now lay a second magnet on the table, with its opposite pole under the chain of nails. You will now find that you can hang on more nails than before; remove the second magnet, and the additional nails will fall off.

Experiment 33.—Vary the experiment by bringing the similar pole of the second magnet under the chain of nails. State the result. Explain, if you can, the reason in each case.

## Reversal of Weak Magnetisation by a Stronger Magnet.

Experiment 34.—Magnetise one of the French wire nails. Observe by means of the compass needle that it slightly retains its polarity, and find which is its N. pole. (Record how you do this.)

Balance the nail on a watch-glass. Bring up N. pole of magnet to N. pole of nail; observe repulsion at a distance. Bring the magnet close up, if necessary holding the nail, and observe that the nail is now attracted.

Experiment 35.—Now test the polarity of the nail again. You will find that the contact with the magnet has reversed it. Again, magnetise a knitting-needle by stroking it once. *Test its* polarity. Now magnetise it in the opposite manner, by stroking it three or four times in the opposite direction with the same pole of the magnet, or in the same direction with the opposite pole. You will now find that the poles of the knitting-needle are reversed.

EXPERIMENT 36.—You may make this experiment with the compass needle itself. By bringing the N. pole of the magnet sufficiently near to the N. pole of the needle you will get attraction.

By suitably stroking you can always magnetise the needle as before.

**Theory of Molecular Magnets.**—You are now in a position to understand the supposition by which physicists have been led to attempt a partial explanation of magnetic phenomena. It is supposed that every molecule of iron is really a permanent magnet,—indefinitely small indeed, but having its two poles; and that, under ordinary circumstances, these magnets are so arranged that each N. pole is joined to a S. pole, while the magnetic axes lie in various directions within the magnet. Thus the action of each pole is neutralised by that of its neighbour, and there is no external effect.

When, on the other hand, the piece of iron is brought under the influence of a magnetic pole, it is supposed that the molecules arrange themselves somewhat as in the figure (Fig. 118), and that then the iron becomes a magnet, the

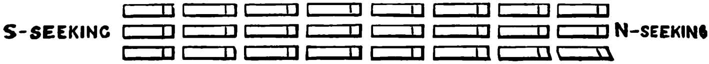

FIG. 118.

unneutralised poles at the end
soft iron the molecules are v
influence of a magnet, and
magnet is removed.

Hard steel, on the other h
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magnets. In this way the coc
is accounted for.

This hypothesis of molec
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wherever we can.

**Evidence in support o**
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This you can verify for you

It is necessary, in the ne
arrangement of small magn
really produce the effect of a

Experiment 37.—This m
beautiful experiment. Let a
parts full with iron filings.
each end of the compass n
horizontally, and stroke it fr
one pole of the magnet, as i
the filings arrange themselves
them, and, since they are n
*each filing* will retain some magneti

On now bringing the test-tube to the compass needle again, you will find that it behaves like a magnet. Shake up the filings and the magnetism disappears. As we cannot suppose that merely shaking the filings destroys their individual magnetisation, we have proof here that a magnet may be imitated by a number of very small magnets arranged in a particular manner, and that the disarrangement of the small magnets may cause the disappearance of its magnetic power.

It is to be observed that the test-tube is not now in the same condition as at first, since the individual filings are now magnets, which they presumably were not at first. But owing to the absence of arrangement, we cannot tell the difference.

## Imitation of Coercive Force.

EXPERIMENT 38.—If you mix a little petroleum or other liquid with some iron filings, you will find that it seems to bind them together into a sort of paste. If you nearly fill the test-tube with some of this paste (some of which may be kept in the laboratory for the purpose), and repeat the last experiment, you will find that the mass is now harder to magnetise, but, when once magnetised, does not nearly so readily lose its magnetisation on shaking. Now the petroleum simply seems to render the filings less free to turn, and thus we get an imitation of the retentive or coercive steel, which confirms our theory. (Water or any other liquid might be used, but it would cause the filings to rust, while petroleum, which contains no oxygen, does not.)

**Effects of Vibration on a Magnet.**—It will now occur to you that by striking a magnet, or otherwise causing it to vibrate, you may be able to disturb the arrangement of its molecules, on which its power depends.

The experiment may be made as follows:—

EXPERIMENT 39.—Take a strongly magnetised knitting-needle; obtain an estimate of its power by the amount of filings it will lift. Now scratch one end several times smartly with a file. Observe now that it is much weaker.

Record by diagrams.

✓EXPERIMENT 40.—Or again, select a strongly magnetised knitting-needle, and having estimated its strength by means of filings, lay two magnets on the table as in the figure (Fig. 119),

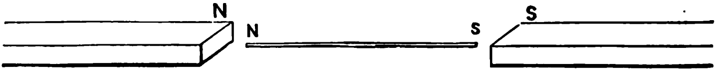

FIG. 119.

and throw down the knitting-needle violently between them, with the poles lying as in the figure.

The jarring of the needle will help the magnets to reverse, or at least weaken the poles of the needle.

EXPERIMENT 41.—An unmagnetised knitting-needle can *be magnetised* in this way, or by scratching with a file while *held close to* one pole of a magnet.

**Influence of Temperature.**—There are many reasons for believing that the temperature of a body depends on the oscillations of its molecules, and that a rise in temperature means an increase in the extent and rapidity of these oscillations.

Hence, if the molecular theory of magnetism be true, we may expect to find that the power of a magnet will be weakened, or even destroyed, by heating, owing to the disarrangement of its molecules.

To test this, make the following experiment.

EXPERIMENT 42.—Magnetise strongly a piece of knitting-needle about 5 cm. long; test its strength by means of filings. Record by a diagram. Heat it strongly, but *not* to a red heat (keeping all magnets at a distance). Test its strength by means of filings (1) while still hot; (2) when cold. Record in each case by a diagram.

Heat a similar strongly magnetised piece red hot. Observe and record in the same way.

EXPERIMENT 43.—Repeat the experiment, this time letting the bar cool while held lengthways between two opposite poles of two magnets. Leave till cold, then test its polarity and its power. Explain.

EXPERIMENT 44.—Heat an iron tack white hot, and observe that while still white hot the magnet will not attract it. Explain.

*N.B.*—This experiment must be made very quickly.

**Additional Evidence.**—In addition to these points, which *you are able to test* for yourselves, it may be mentioned that the hypothesis of molecular magnets receives confirmation from the following observations, which you cannot so easily make for yourselves :—

1. An iron bar becomes slightly longer and thinner when magnetised. If the magnetisation is accomplished suddenly (as it may be by means of an electric current), a curious clink is heard.

2. A magnet cannot have its strength increased beyond a certain point (called the "Point of Saturation"), which would correspond to the greatest possible parallelism of the internal molecular magnets.

**Magnetism of other Substances.**—No other substance exhibits magnetic properties nearly so strongly as iron, but many, indeed most, other substances, especially nickel and cobalt, are freely acted on by a magnet. Some, however, such as bismuth and antimony, are repelled by a magnet. The hypothesis of molecular magnets must therefore be extended to other substances.

It is to be observed that the theory we have mentioned does not profess to account for the magnetism of the molecules themselves.

**On Lines of Force.**—*Definition.*—A field of force is any portion of space traversed by lines of force, *i.e.* pervaded by a force of attraction or repulsion.

For example, the space surrounding the earth is pervaded by a force of attraction towards the earth's centre, and we may imagine lines radiating out from this centre into space (see Fig. 120). The greater the distance from the centre, the more do such lines diverge from one another, and the weaker is the force. Where the force is strong, there the lines of force may be regarded as packed closely together. Since, however, it is necessary to go far above the surface of the earth before the distance apart of the lines of force becomes appreciably greater, *i.e.* before the force of attraction becomes appreciably smaller, we say that near the earth's surface the field of force is nearly uniform.

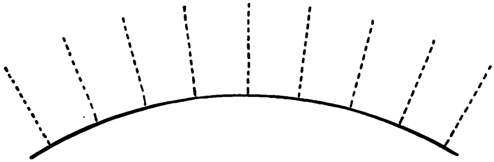

Fig. 120.

If the lines of force were quite parallel, the field would be quite uniform.

**Lines of Magnetic Force.**—Similarly, lines of force may be conceived to radiate from a magnetic pole in all directions through space (see Fig. 121). Where the lines are near together (*i.e.* near the pole), the force is strong; where they are wider apart (*i.e.* further from the pole), the force is weaker.

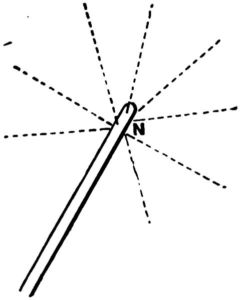

Fig. 121.

A *small* magnetic needle (or piece of soft iron), free to turn in any direction, always sets its length parallel to the lines of magnetic force where it is placed.

EXPERIMENT 45.—Thus if a very short piece of knitting-needle, not more than 1·5 cm. long, be magnetised strongly, and then suspended horizontally with a bit of wax from a shred of unspun silk, which is very light, and has no twist, it may be held near the pole of a magnet, as in the figure (Fig. 122), and will always take up a position parallel to the direction of the magnetic force, and may thus be used for "exploring" the field near the magnet.

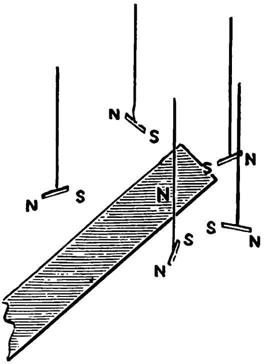

FIG. 122.

EXPERIMENT 46.—It is evident that a piece of soft iron will do as well as a small steel magnet, for it will be turned into a magnet by induction. Repeat the experiment with an explorer made of a small piece of soft iron wire.

*Explanation.*—The force which urges a N.-seeking pole one way will urge a S.-seeking pole in just the opposite direction. If the needle is so short that both ends are practically the same distance from the pole, then the forces on its two ends are equal and opposite, and only tend to turn it round, as in the figures (Figs. 123-126), and not to move it bodily.

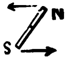

FIG. 123.

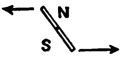

FIG. 124.

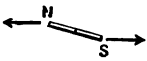

FIG. 125.

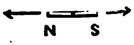

FIG. 126.

The more nearly the needle is in the direction of the line of force the less is the moment or turning power of the "couple" acting upon it, and it will come to rest when it lies exactly in the direction of the force, as in the last figure (Fig. 126).

If the exploring needle were a long one, one end of it would be so much nearer the magnetic pole than the other end, that the attraction would overbalance the repulsion, and the needle would move bodily (indeed, you will notice that, when the exploring needle is hung very near the pole, the silk is pulled appreciably out of the vertical); and, besides, the two poles of the needle would be in different parts of the field, in which the direction of the lines of force might be very different.

**Case of Field due to two Magnetic Poles.**—When there are two (or more) magnetic poles in the field, the force due to the one is superposed on that due to the other, and the direction taken by the exploring needle is that of resultant force.

Experiment 47.—In order to trace the lines of force by means of an exploring needle, lay a magnet on its edge on the table against the face of an upright sheet of paper, or cardboard, as in the figure (Fig. 127), and hold the explorer by

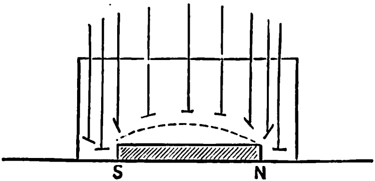

Fig. 127.

means of a shred in the different positions indicated. Observe and record by a diagram the position of the curved lines of force, marking also the position of the two ends of the magnet.

EXPERIMENT 48.—Now lay the magnet flat on the middle of a sheet of paper, and repeat the same experiment in a horizontal plane, exploring the field on both sides of the magnet. Record as before.

EXPERIMENT 49.—Now lay two magnets flat on a sheet of paper in a line with their like poles opposite to each other, and from 4 to 6 cm. apart. Find by means of the exploring needle how to draw the lines of force in the neighbourhood of the two opposed poles in a horizontal plane.

**On the use of Iron Filings in finding the direction of Lines of Force.**—Iron filings make admirable exploring needles, because they are so short. They may be used as follows :—

EXPERIMENT 50.—Lay two magnets in a line on the table, with the N. pole of one facing the S. pole of the other, and at a distance of 4 to 6 cm. apart. Spread a piece of clean writing-paper over them, supporting it quite horizontally. Now strew iron filings slowly and very evenly over the paper near the magnets. Tap the paper, and observe the curves into which the filings collect.

EXPERIMENT 51.—You may obtain a permanent copy of the arrangement of the filings in the last experiment as follows :—

Having obtained the curves clear and distinct, lift up the paper very carefully, remove the magnets and supports from *underneath*, and lay it flat on the table. Now take a second sheet of paper; brush the surface over with a solution of tannin; then place it gently (damp face downwards) on the filings on the first paper. Place a piece of blotting-paper over the two, and press them together gently with the hand all over. Now lift up the second sheet, to which most of the filings will adhere, put it aside to dry, and, when *quite* dry, brush off gently the adherent filings. It will be found that a dark stain is produced wherever a filing has come in contact with the tannin, and in this way an exact copy of the curves can be obtained. Leave the copy with the fair note-book as a record.[1]

EXPERIMENT 52.—Repeat the last experiment with two like poles opposite to each other, and obtain a copy of the curves.

**Law of Magnetic Force.**—*Law of the Inverse Square.*—We will now make an experiment to show that when a magnetic pole A attracts or repels another magnetic pole B, the force exerted between them becomes (like the force of gravity) less, exactly in proportion as the SQUARE of the distance between them is increased.

**Parallelogram of Forces.**—We shall make use of the proposition called the Parallelogram of Forces, viz.—That when two forces, represented in magnitude and direction by the lines AB and AC, act simultaneously at the point A, then their resultant is represented in magnitude and direction by the diagonal AD of the parallelogram of which the two lines AB and AC form the sides.

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[1] For a method by which still more beautiful copies of the distribution of the filings may be obtained, see a paper by A. M. Mayer, *Philosophical Magazine*, 1871, p. 476.

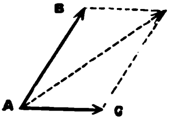

FIG. 128.

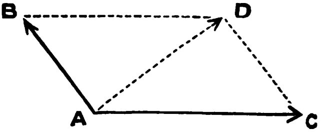

FIG. 129

(See Experiments in Mechanics, Experiment 10.)

EXPERIMENT 53.—Let NS be a strongly magnetised knitting-needle, whose poles, N and S, may, without much error, be supposed to lie (say) half a centimetre from each end. Lay the knitting-needle on a piece of paper, and mark the position of its poles. Let P be a point on the paper whose distance from N is 10 cm., and from S 20 cm. A N.-seeking pole at P would be repelled along the line NP *produced,* and attracted along the line PS.

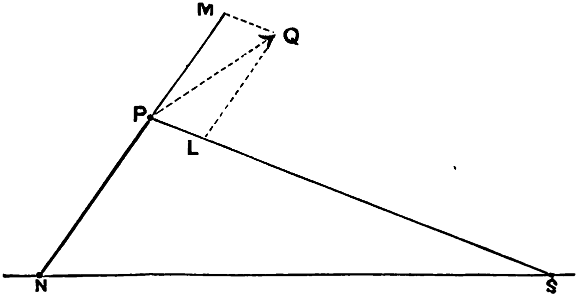

FIG. 130.

Since the poles N and S have equal strength, the force due to S will (if the law of the inverse square be true) be less than the force due to N, exactly in proportion as the *square* of the distance SP is greater than the square of the distance NP.

Now SP=20 cm. ∴ $SP^2=400$
and NP=10 cm. ∴ $NP^2=100$

∴ the force along NP produced is four times greater than the force along PS.

Mark off PM=8 cm. and PL=2 cm. Then PM and PL represent the forces acting at P.

Complete the parallelogram PMQL, and draw the diagonal PQ. Then PQ represents in magnitude and direction the force at P.

Now remove the magnet, and hang an exploring needle at P, and turn the paper till the direction of PQ coincides with that of the needle, *i.e.* till PQ lies in the magnetic meridian. Now restore the magnet to its place, and observe whether the direction of the exploring needle is thereby altered. If it is not, then PQ must be the direction of the force at P, and the assumption of the law of the inverse square on which the calculation was based has led us to the right result. If you repeated the experiment for other points near the magnet, you would obtain a like result, and in this way could prove the truth of the law, for it can be shown that such a result would follow from no other law. What is unsatisfactory in the experiment is the uncertainty that attaches to the exact position of what we call the poles, for the lines of force do not radiate exactly from two points.

**Magnetic Dip.**—When a magnetic needle is accurately balanced, *and free to turn* about a horizontal as well as a vertical axis, it takes up, in most parts of the world, a position inclined to the horizon, indicating that the lines of force due to the earth's magnetism are not horizontal.

EXPERIMENT 54.—In order to show this tendency of one end of the needle to dip, take an unmagnetised knitting-needle, heat the middle red hot, and let it cool slowly. This will soften it, and enable you to file a little nick just where you find the needle will balance on a knife edge placed east and west. Adjust the equilibrium (if necessary) with a bit of wax, so that the end towards the S. shall be very slightly heavier than the other. Then magnetise the needle strongly, turning the lighter end into a N.-seeking pole, and restore it to the knife edge. You will now find that the N.-seeking end appears the heavier, though it is in reality the lighter, showing the way in which the force is inclined.

As a matter of fact, an exploring needle, free to turn in any direction, would in this country dip down, making a considerable angle (about 67°) with the horizontal plane.

### Inductive action of the Earth on Iron at its Surface.

EXPERIMENT 55.—Take a bar of soft iron, *e.g.* the rod of your retort-stand, which you can probably unscrew, and present each end in turn to the two poles of the needle. You will probably find that the rod is already a permanent magnet, the end that has stood lowest being converted into a N.-seeking, and the upper end into a S.-seeking, pole.

Now hold the bar in the magnetic meridian at an angle of about 70° with the horizon (*i.e.* parallel to the direction of the earth's magnetic force), but with its S.-seeking pole downwards and strike the end several times smartly with a hammer. Now test the polarity again. You will probably find that it is now reversed, the earth's influence having been strong enough at the moment when the magnet was jarred to determine the rearrangement of the molecules.

Now hold the bar horizontally, east and west, and hammer it very much; and then test its polarity, holding it all the time horizontal, and east and west, while you present its ends to the poles of the needle. You will now find, by the absence of all repulsion, that the bar is almost completely demagnetised.

Now hold it N. and S., and in the direction of the dipping needle, and, placing the compass needle for convenience near the edge of the table, present (1) the upper end of the bar to the S. pole of the needle, (2) the lower end of the bar to the N. pole of the needle. You will find that the mere change of position has caused the upper end to become a S.-seeking, and the lower end to become a N.-seeking, pole. Now reverse the bar, and again observe, and record the polarity of the ends. The sensitiveness of a bar of soft iron to the earth's inductive action, when tested in this way, is very striking.

# PART VIII.

# STATICAL ELECTRICITY.

(57 *Experiments.*)

# PART VIII.

# STATICAL ELECTRICITY.

[The Student should record in his own words the *object* of each experiment (where this can be stated); the *manner* of making it; the *result observed;* and the *conclusions drawn.*]

EXPERIMENT **1.**—To exhibit electrical attraction and repulsion, tear up a small piece of paper into very little bits and lay them on the table. Rub a dry ebonite rod smartly with a dry flannel held round it in one hand, or on the coat-sleeve, and then hold the rubbed rod close over the fragments of paper: these will fly up to it, and some may be seen to stick to the rod, while others again dance up and down between the rod and the table. Almost any small light objects, such as chips of matchwood, or cork, or pith, or bran, will serve as well as the paper. The ebonite rod is said to be "electrified." In very dry weather the rubbing is often attended with a crackling sound, and in the dark sparks may be seen to be emitted.

Many other substances behave in the same way when rubbed, and one of the first in which the property was observed was amber, called by the Greeks "electron," a name from which such words as "electricity," "electrify," etc., are derived.

EXPERIMENT 2.—The ebonite rod after being rubbed really attracts large and heavy bodies, besides small light fragments of paper, etc., but not with sufficient force to lift them. If however a pencil be balanced horizontally on a watch-glass, it will readily move under the attracting force of an electrified rod of ebonite.

EXPERIMENT 3.—Conversely, if the ebonite rod be rubbed at one end, and then laid on the watch-glass, it will be in its turn attracted towards the finger or towards a pencil held near the rubbed part.

To show that the force with which the electrified ebonite attracts the pencil is exactly equal to that with which the pencil attracts the ebonite, let the two be laid side by side on a watch-glass inverted upon a second watch-glass, as in the figure (Fig. 131).

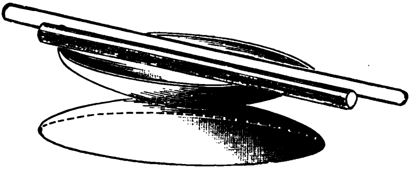

FIG. 131.

There is now no motion, showing that the force with which the ebonite pulls the pencil, and with it the watch-glass, is balanced by the force with which the pencil pulls the ebonite, and with it the watch-glass, round in the opposite direction.

This is an instance of the law, which is believed to be universal in nature, that to every action there is an equal and *opposite* reaction.

EXPERIMENT 4.—A pith ball hung by a cotton thread is very readily attracted towards an electrified rod, and this, or (better, perhaps) a straw balanced on a watch-glass, serves as a convenient "electroscope" to tell when a rod is electrified.

EXPERIMENT 5.—Now let an ebonite rod be electrified by rubbing with flannel, and balanced on the watch-glass or in a stirrup of wire bent as in the figure (Fig. 132), and suspended by two cotton threads near together, then let a second rod of rubbed ebonite be presented to the rubbed end of the first. *Repulsion* will be observed.

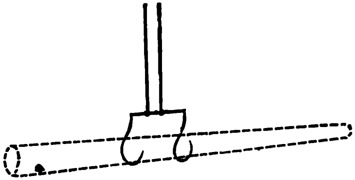

FIG. 132.

EXPERIMENT 6.—Now take a rod of sealing-wax and rub one end with dry flannel—taking care not to break the sealing-wax; observe that it too becomes electrified, will attract bits of paper or the balanced straw, and is itself attracted by the finger when balanced on the watch-glass after rubbing.

EXPERIMENT 7.—Observe also that when electrified it repels an electrified ebonite rod, and, in fact, behaves just like a rod of ebonite *when rubbed.*

Q

Experiment 8.—Now take a *dry* glass rod, and rub it in the same way with a piece of dry silk. It is usually less easy to electrify glass than sealing-wax or ebonite, especially in damp weather, on account of the readiness with which glass condenses water-vapour on its surface and becomes damp, and it is best to warm the glass, as also the silk. A bright fire is best for this purpose. If a gas flame is used, it must be remembered that water-vapour is one of the products of combustion of coal gas, and that as long as the glass is cool it will condense some of this on its surface, and so will at first get damper rather than drier. After it is thoroughly warmed, however, it will get drier. On being smartly rubbed with the silk, the dry glass becomes strongly electrified, as is shown by the attraction of light bodies, the balanced straw, etc. And it might be concluded that the electrified glass was in the same state as the electrified ebonite or sealing-wax. But the following experiment shows that this is not the case.

Experiment 9.—Electrify a rod of ebonite at one end by rubbing it with flannel; balance it on a watch-glass. Electrify a rod of glass by rubbing with silk, and present it to the electrified end of the ebonite. *Attraction* will take place. This shows that the electrification of the glass is different from that of the ebonite or the sealing-wax.

Experiment 10.—Again electrify a glass rod, hang it in the stirrup, and present to it in turn a similarly rubbed glass rod, and a rubbed ebonite rod. Observe and record the results.

Now it is found that any substance that has been electrified by friction so as to attract light unelectrified objects, such as *bits of* paper, etc., behaves towards a piece of rubbed ebonite either like the rubbed glass or like rubbed ebonite, so that the electrification produced in a body by rubbing is apparently always one of two kinds.

**Definitions.**—The electrification generally produced on glass by rubbing it with silk is called Vitreous (from *vitrum*= glass), or, for greater convenience, Positive (+ve). That produced on resin or ebonite by rubbing with flannel or fur is called Resinous or Negative (−ve) electrification.

Sometimes we express the fact that a substance becomes resinously or −vely electrified when rubbed by saying that it receives a "charge" of −ve electricity; while, again, we may speak of a charge of +ve electricity. It would, however, be better to speak only of *electrification*, and not at all of *electricity*. It was formerly thought that the electrification of a body was due to its being covered with a coating of + or — electricity, which was supposed to be a weightless invisible fluid; or that all bodies were coated with a certain amount of "electricity," but that a +vely electrified body had more than usual, a −vely charged body less than usual. Now we shall find that the "state of electrification" does very often "flow" from one body to another, and that in this respect it may be regarded as a fluid; while again a body does not weigh more or less when electrified. If we always interpret "electricity" as "electrification," we may use the word without its misleading us.

**Summary.**—The results which we have at present obtained may be summed up by saying that—

All electrified substances attract unelectrified bodies;
Similarly electrified substances repel each other;
Dissimilarly electrified substances attract each other.

## Electrification communicated by Contact.

Experiment 11.—Hang up a pith ball by a thread of undyed silk, and present to it an electrified rod of glass or ebonite.

The ball is at first attracted to the rod, but after touching it is repelled.

Experiment 12.—The ball will now attract and be attracted by an unelectrified object, such as the hand, if held sufficiently near it, and is therefore said to have been electrified by contact with the rod, or to have received a charge by contact.

Instead of a pith ball, the end of the silk thread itself may be used.

It is evident, since the ball remains charged, that the electrification does not pass away along the silk thread, or at least not rapidly.

Experiment 13.—We can convince ourselves of the fact that the electrification has not spread far up the silk by holding the rubbed ebonite rod near to the thread, a foot or more above the ball; the thread will be *attracted* at first, showing that it is not yet electrified, but, after rubbing against the rod, the silk will become charged by contact, and will then be repelled.

Now it will have been observed that when the pith ball was suspended by a *cotton* thread (especially if the thread were damp), the ball was always attracted towards the charged rod and never repelled. We will now show that *the reason* of this is that the electrification given to the ball by contact spreads along the damp cotton, and passes away along it to the support from which it hangs, and so to the earth.

EXPERIMENT 14.—To prove this fasten the pith ball to a piece of cotton about 18 inches long, or make a loop of cotton of about this length, and let this hang from a piece of silk. Now present an electrified rod to the ball or the lower end of the noose; this will at first be attracted, and afterwards repelled. Then hold the charged rod near the cotton thread a foot or more from the ball or lower end. The thread is repelled, showing that the electrification given to the ball has spread to the thread. Now present the electrified rod to the silk above the cotton, and you will find that it is at first attracted, showing that the electrification has not spread up the silk.

*N.B.*—For this experiment to be successful, it is necessary to singe off all the projecting fibres of the cotton by passing it rapidly through a flame, since, as we shall see afterwards, an electric charge very readily escapes from sharp points into the air.

**Definition.**—A substance along which electrification spreads and passes away is called a **conductor** of electricity; a substance along which electrification does not spread is called a **non-conductor**, or **insulator**, since such a substance may be used for insulating or isolating an electrified body so as to prevent its electrification from passing away.

Thus we have found that silk is a non-conductor of electricity, while cotton is a conductor.

Since it is only the rubbed part of the ebonite or glass rod *which becomes electrified*, it is evident that these substances are non-conductors of electricity, for the charge does not spread along them to unrubbed parts.

We shall show afterwards that the rate at which electrification spreads and passes away along different substances is very different. Along metals electrification spreads with extreme rapidity; along such substances as cotton or dry wood less rapidly; along silk or ebonite very slowly indeed.

The following is a list of substances arranged in order of conductivity:—

| | |
|---|---|
| Silver,<br>Copper,<br>Other metals,<br>Charcoal,<br>Water in its ordinary state of purity, | Good Conductors. |
| The body,<br>Cotton,<br>Dry wood,<br>Marble,<br>Paper, | Partial Conductors. |
| Oils,<br>Porcelain,<br>Wool,<br>Silk,<br>Resin,<br>Gutta-percha,<br>Shellac,<br>Ebonite,<br>Paraffin,<br>Glass,<br>ry air, | Non-conductors or Insulators. |

The fact that water is a good conductor and dry air a bad one explains why it is necessary for many electrical experiments that the air and apparatus should be dry.

If a rod of ebonite or glass is much handled, it may lose its insulating power, becoming coated with a film of moisture, which readily conducts the charge; and experiments sometimes fail through the hands of the experimenter being hot and moist. Glass is a hygroscopic substance, and tends to condense moisture on its surface much more rapidly than ebonite; hence the latter is much more easy to electrify in damp weather.

## Difficulty of discharging an Insulator.

EXPERIMENT 15.—It is to be noticed that an electrified insulator cannot be discharged by touching it in one place, for this only removes the charge of the part touched. It must be touched all over to be completely discharged.

## Discharge by means of a Flame.

EXPERIMENT 16.—The best way of completely discharging a rod of glass or ebonite is to pass it rapidly through or over the flame of a Bunsen's burner, which is a very good conductor.

EXPERIMENT 17.—It will be found that a pith ball is a sufficiently bad conductor to be difficult to discharge without touching it all over. A metal ball, on the contrary, is discharged at once when touched with the finger, as also is a pith ball which is gilded or covered with tinfoil.

Make the experiments as follows. Hang a pith ball by a *dry silk thread.* Touch it with an electrified rod till the rod repels it. Remove the rod, and touch the ball with the finger. Now present the electrified rod again. If there is any sign of repulsion, it shows that the ball has not been completely discharged.

EXPERIMENT 18.—Now repeat the experiment with any small light metal object instead of a pith ball. Observe and record the result. Try the effect of just touching the suspended metal object (*a*) with a piece of metal, (*b*) with a piece of damp cotton, (*c*) with a piece of dry cotton, (*d*) with a rod of glass or ebonite that has not been recently rubbed or dried, (*e*) with a piece of ebonite that has been well rubbed and then discharged in a flame; and record and explain the result in each case.

In this way you will learn what great care is necessary to prevent the electrification of a charged conductor, such as the piece of metal, from passing away to the earth.

It is well, too, not to handle the silk thread more than is absolutely necessary, lest it become damp or dirty, when it will cease to insulate.

EXPERIMENT 19.—A pith ball attached to an insulating silk thread is a much more useful el [illegible] which is hung by a cotton thread; [illegible] means we can tell, not only whether an object is electrified or not, but also whether it is electrified +vely or —vely.

Thus, if the pith ball has been electrified, say, —vely, to begin with, by contact with rubbed ebonite, and an object is presented to it which repels it, we know that the object is electrified like the ball, *i.e.* —vely.

If [illegible] the other hand, the ball is attracted, we know that the [illegible] either not electrified at all, or is electrified +vely.

If the attraction is much stronger than that which is produced by presenting an unelectrified body, such as the hand, to the ball, then we may conclude that the object is +vely charged, but it is safest to make sure of this by means of a second silk-hung pith ball, which has been charged +vely, to begin with, by contact with rubbed glass. If the body be +vely charged, this ball will be repelled by it.

EXPERIMENT 20.—Take a short strip of writing-paper about an inch wide, warm it, and then rub it smartly with a piece of warmed india-rubber (or, better, between two india-rubber finger-stalls, placed on the thumb and fore-finger). Now test the electrification of the paper by means of two silk-hung pith balls, one of which has been charged +vely and one —vely. Explain fully how you do it, and the result.

EXPERIMENT 21.—Now repeat the experiment, using two india-rubber finger-stalls, but present this time, not the paper, but one of the finger-stalls, to the charged balls, and observe that it is electrified in an opposite manner to the paper.

[illegible] **production of equal and opposite** or beeswax on to an [illegible] know how to insulate a body, and prevent its charge from escaping, we can show that in *all* cases in which we rub dissimilar substances together,

(1) The rubber, as well as the rubbed body, receives a charge;

(2) The charges on the rubber and the rubbed body are of opposite kinds,

(3) That the two opposite charges or electrifications are *equal in amount.*

EXPERIMENT 22.—If, after rubbing an ebonite rod with flannel in the ordinary way, we test the flannel for a charge, we shall find no trace of electrification on it; but this is because the flannel is itself a conductor, and is held in the hand, so that the charge escapes to the earth as fast as it is produced. If, however, we tie a small piece of flannel to the end of a dry ebonite rod, and then, using the rod as a handle, rub a second piece of ebonite with the flannel, the charge on the flannel cannot pass away, and we are able to verify the statement that it becomes charged, and that the charge is of the opposite kind to that on the ebonite.

EXPERIMENT 23.—To prove that the two opposite charges are equal, we can present simultaneously both the insulated flannel and the rubbed end of the ebonite to the charged pith ball, without separating them, when no effect will be produced. On removing one of the two, the other will attract or repel the ball. A more accurate proof will however be given in Experiment 52.

EXPERIMENT 24.—The experiment should be repeated with silk and glass; the silk rubber being insulated on an ebonite handle in the way described.

EXPERIMENT 25.—The electrification produced on glass and india-rubber, when the two are rubbed together, may be tested in the same way. In this case, if the india-rubber is dry, it is not necessary to insulate it.

**Substances arranged in electrical order.**—It is found possible to arrange all substances in a list, so that when any *two* are rubbed together, the one which comes earlier in the list becomes +vely charged, while that which comes later becomes −vely charged. The following is such a list :—

Fur, wool, resin, glass, silk, metals, sulphur, india-rubber, gutta-percha, collodion.

The order, however, is not trustworthy under all circumstances of weather, etc., for it sometimes happens that glass rubbed with silk or flannel is similarly electrified to ebonite rubbed with silk or flannel. The part played by the air in determining the sign of the electrification is not yet understood.

**The Proof Plane.**—A small metal disc fastened to an insulating handle, when placed in contact with a charged body, becomes for the time being, from an electrical point of view, part of the body with which it is in contact, and becomes charged in the same manner as that part. Such a disc is called a Proof Plane, and is a most useful instrument for testing both the kind and quantity of charge at any part of the surface of a charged body. A convenient proof plane may be made by sticking a threepenny piece with sealing-wax or beeswax on to an ebonite rod, the end of which should be filed flat.

EXPERIMENT 26.—As a preliminary exercise in the use of the proof plane, place it against a piece of rubbed ebonite, and then test the charge carried away by means of a −vely charged pith ball electroscope. Care should be taken not to damp the handle of the proof plane by fingering it, but to hold it by the extreme end, and occasionally to dry it over *the Bunsen flame.*

## Electrical Influence or Induction.

EXPERIMENT 27.—Armed with the proof plane, we are now in a position to obtain more insight into the nature of Electrical Attraction and Repulsion, for, by applying it in the manner indicated in Figs. 133 and 134, we can show that while an electrified rod is held near an insulated conductor (such as a file hung by two silk threads), (i.) the end *nearest* the rod is charged in an *opposite* manner to the rod, while (ii.) the end *furthest* from the rod is charged in the *same manner as* the rod; while (iii.) between the two ends of the

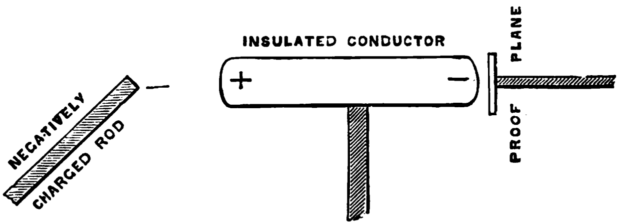

FIG. 133.

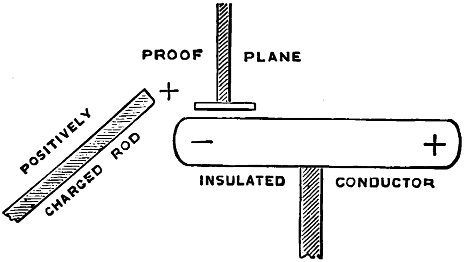

FIG. 134.

*Note.*—It will be observed that in these drawings insulating substances are distinguished from conductors by being shaded.

conductor near which the charged rod is held, a region can be found where there is no charge. You should find by experiment, and show by a diagram, the position of this neutral region, or region of no charge in your file.

From these experiments it appears that the electrified body *induces* in the insulated conductor near it an opposite charge on the near side, a similar charge on the far side; and since oppositely electrified bodies attract, and similarly electrified bodies repel, each other, it is clear that, owing to the difference of distance, the attraction for the near end will prevail over the repulsion of the remoter end

### Disappearance of Charges on removal of the Inductor.

Experiment 28.—If the inducing body or inductor, as the charge rod is called, be now removed, the two opposite electrifications on the insulated conductor completely disappear, and the body shows no signs of charge, provided that the charges removed for testing by the proof plane are insignificant in amount. It appears from this that, on removing the charged inductor, the two opposite states of electrification spread evenly over the whole conductor, and exactly neutralise each other.

### Solid Non-conductors not attracted.

Experiment 29.—If our conclusion is correct, that electrical attraction depends, in the first instance, on the separation of charges under the influence of the attracting body, it should follow that a non-conductor in which the charges *cannot flow* is not attracted. Make the experiment by suspending a rubbed ebonite rod in a silk-hung stirrup, and then presenting to it a second ebonite rod, that has been well dried by rubbing and then completely discharged by a flame. You will find that there is no attraction.

### Liquid Non-conductors attracted.

EXPERIMENT 30.—If, however, you hold a charged ebonite rod close to the surface of some petroleum, which we shall find (Experiment 38) is a non-conductor, the liquid will rise below the rod as if attracted, and as if a separation of charges took place.

### Charging by Induction.

EXPERIMENT 31.—Let us now vary the previous experiments. Bring a charged rod up to an insulated conductor, as before. While the rod is near, let the conductor be touched by the hand, so that it is for a moment connected by a conducting body with the earth. Now remove the hand, keeping the inducing rod in its place. The conductor will now be found, on testing, to be charged all over with the opposite kind of charge to that of the inducing rod; and, if the inducing rod be removed, it will be found to be permanently charged.

It seems that in this case the similar charge, which in the last experiment was driven to the other end of the insulated conductor, is now driven completely away, presumably to the other end of the earth.

This process is called "charging, by induction."

**Like charges repel, while unlike attract, each other.**—It appears from the last two experiments, in which the shifting of charges in conductors has been observed, that the behaviour of the electrical states, which we call charges, ay be expressed by saying that like charges repel, while unlike charges attract, each other. And when the charge cannot leave the conducting matter, the matter itself tends to move with the charge.

We are now in a position to explain two instruments of great use whose action depends upon induction.

**Gold Leaf Electroscope.**—The first is the Gold Leaf Electroscope. A simple and very efficient form, that you may easily construct for yourself, is that shown in the diagram (Fig. 135), in which two very thin gold leaves (A A) are attached to a little tinfoil-covered slip of wood, into which is stuck the thick copper wire (BC) to the top of which a penny is soldered. The wire passes through a piece of sealing-wax (DE), which is stuck across the mouth of the funnel-shaped flask that serves to protect the leaves from draughts. The sealing-wax serves to insulate the rod BC. The penny at the top will be referred to in future as the "knob" of the electroscope, or sometimes as the "plate." The letters G. L. E. will sometimes be used to signify Gold Leaf Electroscope.

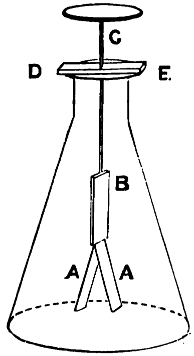

FIG. 135.

It should be noticed that the glass of the flask is nearly always so damp or dusty as to act as a conductor in connection with the earth through the table on which it stands, and that the insulation of the leaves is due solely to the sealing-wax, which can at any time be cleaned and dried by the flame of a Bunsen burner.

### Method of Charging the G. L. E. by Induction.

EXPERIMENT 32.—On bringing near the knob of this *apparatus a charged* rod, the leaves diverge widely, owing to the separation of charges in the rod and leaves, a charge like that of the rod being repelled to the remote end of the metal, *i.e.* into the leaves, while the opposite kind is attracted to the nearer end, *i.e.* to the knob.

If the knob be now touched by the hand, so as to be put to earth, the rod being still kept in its place, the leaves collapse almost entirely. For the metal mass being now connected with the earth, the charge, like that of the rod, is driven to earth, and the whole is charged in the opposite way, but most strongly near the inducing rod, and only slightly in the leaves which are remote from it.

If we now remove the inducing rod, the opposite charge, which it has hitherto held bound by its attraction on the near side of the knob, spreads .itself over the whole metal piece, and, reaching the leaves, causes them to repel each other and diverge widely.

The apparatus has, in fact, been charged by induction, exactly as was the metal conductor in Experiment 31.

The apparatus thus charged is very sensitive to the approach of a charged body.

## Interpretation of the indications of the G. L. E.

EXPERIMENT 33.—If a body charged similarly to the leaves approaches the knob, the leaves diverge more widely, as if a further charge was driven into them.

EXPERIMENT 34.—On the other hand, when a body charged oppositely to the leaves approaches the knob, the leaves collapse, as if their charge was either withdrawn or counterbalanced by an opposite charge being driven into them.

EXPERIMENT 35.—If, however, the charged body whose approach causes the leaves to collapse be brought still nearer to the knob without touching, the leaves will diverge again, this time with the same kind of charge as that of the charged body.

### Influence of large Conductor.

EXPERIMENT 36.—It is to be observed that the leaves collapse on the approach of any large unelectrified conductor, such as the hand, for this, being acted upon by the electrified mass of metal, becomes oppositely charged on the near side by induction, and the charge thus induced reacts on the charge of the metal, withdrawing it from the leaves, and holding it bound or condensed on the nearest side of the knob.

**Collapse of the leaves does not necessarily indicate charge in the body tested.**—Hence it is very important to notice that the *collapse* of the leaves does not necessarily indicate that the body being tested is charged, but may merely indicate that it is a conductor, so that increased divergence is a much surer sign of charge than diminished divergence.

EXPERIMENT 37.—Since the gold leaf electroscope is a much more sensitive instrument than the suspended pith ball, we may use it for some experiments on conductivity, for which the latter was not suited. Thus: Rub the end of an ebonite rod so as to electrify it. Dip it into water and withdraw it immediately; observe that it is now completely discharged

Experiment 38.—Now after drying and re-electrifying the end of the rod, dip it for an instant into a beaker of petroleum; observe now that it still retains much of its charge. Now repeat, but keep it submerged for a longer time (say five or ten seconds) under the petroleum. Observe, record, and explain the results.

Experiment 39.—Again, after charging the electroscope, touch the knob for an instant with a piece of india-rubber, a silk thread, a dry cotton thread, and with other substances that have been well dried, and in this way compare their conductivity by observing how much the leaves collapse.

Experiment 40.—We can also show how very readily ebonite becomes electrified by friction. Thus, after drying a rod of ebonite, and discharging it in a flame, let the end be ever so slightly rubbed against anything, or touched with the finger, it will be found to be electrified.

Experiment 41.—Try, however, the effect of rubbing one dry and unelectrified ebonite rod with another, also dry and uncharged.

**Note on the Electrophorus.**[1]—It is important to remember—

(1) That the charge produced on the surface of the ebonite by rubbing acts by induction through the ebonite on the conductor below (either a metal sole or the table).

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[1] In the case of a class of pupils learning Electricity for the first time, a *vivâ voce* description and demonstration of the use of the electrophorus should be given.

(2) That the opposite charge induced in the "sole" reacts on the charge on the ebonite and prevents its escape.

(3) That the cover is not really in contact with the ebonite at more than a few points, so that, since the ebonite is an insulator, the charge given to the conductor by contact is extremely small.

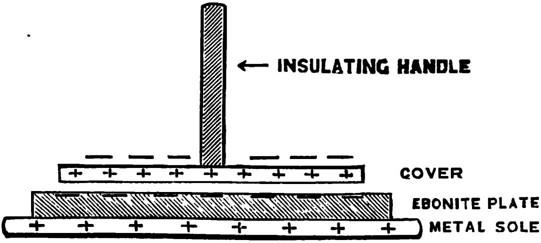

Fig. 136.—Condition of the Electrophorus *before* touching with the finger.

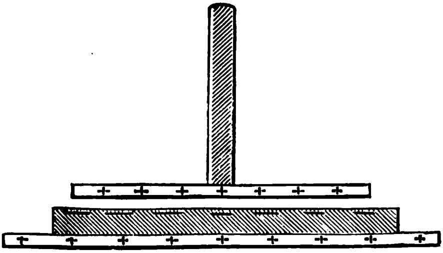

Fig. 137.—Condition of the Electrophorus *after* touching with the finger.

(4) That the cover is really charged by induction through the thin film of air which separates it *from the ebonite.*

(5) That the object of touching the cover with the hand is to allow the negative charge, which is repelled by the inducing charge on the ebonite, to escape to earth.

The two diagrams on page 259 are a sufficient memorandum of the construction.

EXPERIMENT 42.—In order to convince yourself that it is not by contact with the ebonite (or india-rubber) plate that the electrophorus cover gets its charge, lay the cover on the rubbed plate, and then, *without touching it with the finger*, remove it to the electroscope, and test the sign of its charge. You will find it to be of the *opposite kind* to that of the plate with which it has been in contact; in fact, that the cover has been charged by induction, though not put to earth. This is because the insulation of the handle is not perfect. If the handle be very carefully dried, and the experiment performed very rapidly, you will find that it comes away less strongly charged when not put to earth.

In using the electrophorus, it is very important, especially in damp weather, to thoroughly dry the handle and the ebonite or india-rubber, which may with advantage be warmed with a Bunsen gas flame. Also the handle should be laid hold of as far away as possible from the metal plate.

EXPERIMENT 43.—The electrophorus enables us to obtain more powerful electrical effects than before, and it is well to repeat with its aid, and with the more sensitive gold leaf electroscope, instead of the pith balls, the experiments on induction, viz. 27, 28, and 31.

## On the Distribution of Electrification on Insulated Conductors.

EXPERIMENT 44.—Let the electrophorus disc be charged and held away from other conductors, and then let the proof plane be applied to the middle, and let its charge be communicated to the electroscope, and the divergence caused in the leaves be observed. Next, after discharging the electroscope, let a charge be taken by the proof plane from the edge of the disc, and again communicated to the electroscope. It will be found that the charge brought from the edge is much greater than that from the middle.

*N.B.*—We cannot accurately compare two different charges brought by the proof plane to the electroscope, since the divergence of the leaves is not proportional to the charge. But we may obtain some notion of the relative magnitude of the charge at different parts of the disc, by observing how many charges brought by the proof plane from one place produce the same effect as one (or more) brought from another place. Used in this way our electro*scope* becomes an electro*meter*.

EXPERIMENTS 45, 46, 47.—Now let a similar experiment be made with the silk-hung file, *i.e.* let the file be strongly charged by the electrophorus, and then let charges be removed for examination, first from the middle of the flat side of the file, then from one edge of the file near the middle, then from the extreme end. Let the effects on the electroscope be compared. It will be found that the charge is greater at the edges than on the flat side, but that it is greatest of all at the pointed ends. And if similar experiments be made on other *insulated conductors, it* will be found that the charge is always greatest at projecting points and edges, and that only in the case of a sphere hung away from other conductors is the charge uniformly distributed over the surface.

**Electric Density.**—This is sometimes expressed by saying that the "electric density" on any charged conductor is greatest at projecting points and edges, a result which may be represented graphically, as in the following diagrams.

*Representation of Distribution of Charge on insulated Conductors of various shapes remote from other Conductors.*

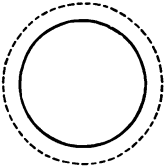

Fig. 138.

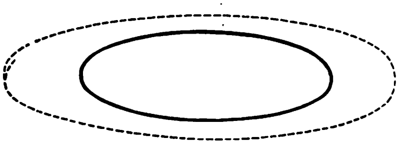

Fig 139.

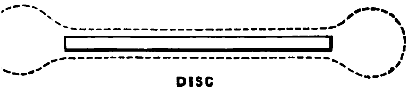

Fig. 140.

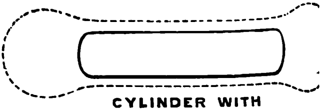

Fig. 141.

Accurate measures have shown that the distribution of electrification over a charged insulated conductor, removed from the influence of other conductors, depends only on the shape, and not at all on the size, of the conductor.

*N.B.*—Since the distribution of charge on a conductor depends on its shape, it is evidently important always to apply the proof plane in the same way to the electroscope, and to let it lie flat (where possible) against the conductor whose charge *is being* measured, so as not to alter the shape of the latter.

**Absence of Charge in the interior of a Conductor.**—Just as a charge collects on the projecting edges and points of an insulated and isolated conductor, so, on the other hand, is there no charge whatever in the interior of such a conductor, as is shown by the following experiments.

EXPERIMENT 48.—Place a deep metal vessel on an insulating ebonite slab; electrify it strongly by means of the electrophorus. Plunge the proof plane to the bottom, and withdraw it again, taking care that it does not touch the edge. You will now find that it has brought away no charge. Apply the proof plane to the edge of the vessel, and it brings away a strong charge.

EXPERIMENT 49.—Take two similar pill-boxes, one full of shot, and the other empty. Make an insulating stand of two ebonite rods, held horizontally side by side, by the retort-stand clip, as in the figure (Fig. 142), and on these place the

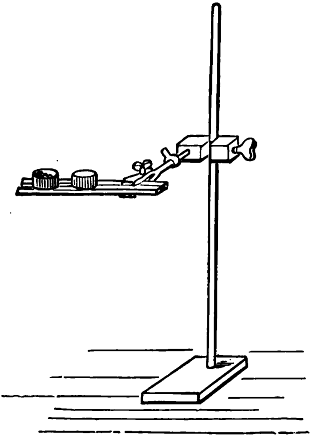

FIG. 142.

two boxes side by side. Charge one by means of the electrophorus. Then, by means of a third ebonite rod, bring the two boxes into contact. Then separate them as widely as possible, and show by means of the proof plane that the two boxes are equally charged. This proves that a conductor takes away just the same charge, under similar circumstances, whether it be hollow or solid.

EXPERIMENT 50.—Make the experiment of placing the metal vessel on the electroscope plate, charging it, and then rapidly pouring in shot, so as to make it practically solid, and observing whether any alteration is produced in the divergence of the gold leaves. (*N.B.*—Care must be taken that the pellets of shot do not follow each other so closely as to form a continuous chain, which would connect the electroscope with the hand, and thus discharge it.) State and explain the result.

EXPERIMENT 51.—If the deep metal vessel be placed on the electroscope plate and left uncharged, and if then a charged insulated body (*e.g.* a small weight hung by a silk thread, or the proof plane) be gradually lowered into it, the leaves will be seen to diverge more and more widely, till the charged object is well inside the vessel, after which the divergence is not increased. If now, taking care not to let the object touch the sides, you test the sign of the charge on the leaves, by means of a +vely or −vely charged rod, you will find that their charge is of the same sign as that of the charged object inside the vessel. This shows that the charge *on the object,* acting by induction, repels a similar charge to the outside of the vessel and to the leaves, and attracts an opposite charge to the inside, which is held bound there as long as the object remains inside the vessel.

If now the object be withdrawn without touching the sides, the induced charges will re-combine, and the leaves will collapse.

But if, instead of being withdrawn, the object be allowed to touch the side, no change is observed in the divergence of the leaves; only, on now withdrawing the object, it will be found to be completely discharged, while the divergence of the leaves remains undiminished. This shows that the opposite charge induced on the inside of the vessel was exactly equal to the inducing charge on the object, since, when the object touches, and so becomes part of, the vessel, these two opposite charges exactly neutralise each other.

This result is very important, for it shows that when an insulated charged object is introduced into a room, it induces on the walls of the room an opposite charge, which is exactly equal to that on the object.

**Tests of Equality of Charge.**—Two insulated conductors are said to have equal and opposite charges, when, after putting them in contact with each other, neither is found to possess any charge.

Also we learn that in order that a charged body may give up *the whole of its charge* to another, it must be put entirely inside the other.

Thus if two charged bodies of different sizes or shapes are made *to touch the plate* of the electroscope, and if the leaves diverge equally in each case, it does not follow that the two charges are equal. For, owing to the difference of shape or size, the one will, after contact, retain more of its original charge than the other. But if on dropping each in turn into a deep metal vessel standing on the electroscope, the effect is the same, then we know that the charge on each was the same.

From the definition of equal charges just given, it is evident that if two insulated conductors have *opposite* charges, we can at once tell which is the greater: for suppose A to be charged +vely and B −vely; put the two in contact, and then examine the sign of the charge on either. If it is positive, then A's was the greater charge; if negative, then B's was the greater.

## Accurate proof of the Equality of the opposite Charges produced by Friction.

EXPERIMENT 52.—Fit a small roll of dry flannel at the bottom of your deep metal vessel, leaving it only just loose enough in the middle to admit the end of an ebonite rod. Now place the vessel on the plate of the electroscope, insert the (dried) ebonite rod into the middle of the roll, and twist it about between the thumb and finger, so as to electrify it by friction with the flannel; you will observe *no* divergence of the leaves, indicating *either* that no electrification is produced at all, *or* that just as much +ve is produced as −ve. Now withdraw the rod, and the leaves immediately diverge, showing that the latter supposition is the right one.

EXPERIMENT 53.—Fasten by means of gummed paper a strip of tinfoil to two ebonite rollers, as in the figure (Fig. 143).

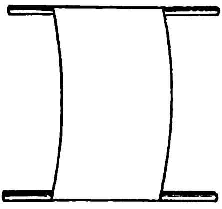

FIG. 143.

Charge the sheet by means of the electrophorus. Then take a charge from the middle of the lower edge of it with the proof plane, and observe the divergence of the leaves. Now roll up the sheet on the upper roller, and again take a charge from the same place. Observe and explain the result.

*N.B.*—Care must be taken to keep the insulating rollers thoroughly dry, and in rolling up the sheet only the tips of the rollers should be handled.

**Dissipation of Charge.**—It is easily shown that a strongly charged body loses its charge more quickly than one less strongly charged.

For example, the gradual collapse of the electroscope leaves is quickest when it is strongly charged.

At points and edges a discharge often takes place into the air, and, if the body be strongly charged, a wind is felt proceeding from any projecting point. This effect is, however, not easily obtained without an electrical machine.

EXPERIMENT 54.—The experiment may be made of placing a number of needles on the electroscope plate with the points projecting, then charging the electroscope, and *observing the rapidity* with which the leaves collapse. Now repeat the experiment in precisely the same way, only without the needles. It is said that the thorns and hairs with which certain plants are armed aid the escape of an electrical charge better than any artificially made points. You should make trial of some. Try also to electrify a piece of cotton from which the projecting fibres have not been burnt off, hanging the cotton from a silk thread.

## Distribution of Charge disturbed by the presence of neighbouring Conductors.

EXPERIMENT 55.—To prove that when an uninsulated conductor is held near a charged insulated conductor, the charge on the latter induces an opposite charge on the near side of the former, which in turn attracts towards it the charge on the insulated conductor so that the distribution on the latter is disturbed, charge the silk-hung file (or some other insulated object), then hold near one end of it the hand, or any other uninsulated conductor. Apply the proof plane to the side of the latter nearest the file, remove the charge to the electroscope, and show that it is of opposite sign to the charge on the file. This proves the first part of *the above* statement.

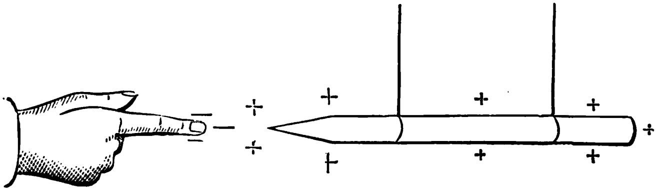

FIG. 144.

To prove the second part, take a charge with the proof plane from the end of the file near the hand, and observe its effect on the electroscope; then do the same again after removing the hand. Now test the end of the file remote from the hand in the same way. Represent by diagrams the distribution of the charge on the file (1) when no conductor is near, (2) when a conductor is near one end.

The following experiment is an instructive one.

EXPERIMENT 56.—Place two vertical insulated metal discs, A and B, opposite to each other, and let each be connected by a wire with an electroscope. Midway between the two introduce a *charged* insulated disc C, the sign of whose charge is known. Observe the divergence of the electroscope leaves. Test the sign of the charge on each. Now touch both A and B with the finger. Observe and explain the result. Now move C nearer B. Observe that the leaves of each electroscope diverge. Test the sign of the charge on each. Explain in your own words.

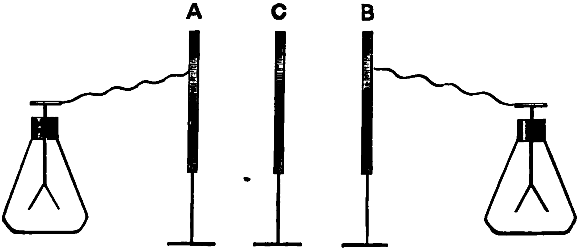

FIG. 145.

EXPERIMENT 57.—We have shown that, when a conductor is charged, the charge is only on the outside surface, and we can now show that a body surrounded by a conductor is completely screened from all electrical influence.

Place your electroscope inside a cage made of a roll of wire gauze. You will now find that the electrophorus plate or a charged rod may be brought quite close to the cage, and even discharged on it, without the electroscope leaves being in the least affected.

# PART IX.

# CURRENT ELECTRICITY.

(16 *Experiments.*)

# PART IX.

# CURRENT ELECTRICITY.

THE simple forms of Wheatstone's Bridge and Rheocord required in the following experiments are those described in Appendix A of Professor Guthrie's *Magnetism and Electricity.* The astatic galvanoscope there described is rather difficult for boys to construct, and may for beginners be replaced with advantage by one made in the following manner. When experiments made with this have created a desire for a more sensitive instrument, then the exchange should be made.

**Description of an easily constructed Galvanoscope.**—A A is a wooden block about 12 cm. (5 inches) square and 1·5 cm. ($\frac{3}{5}$ inch) thick, the under side of which is armed at the corners with four little sharp spikes, B, B, B, which, on the application of gentle pressure, stick into the table, and prevent the block from slipping. In the middle of the block a hole is bored, which is filled by a cork, through which is passed the point C of a fine sewing-needle, projecting about a cm. above the block, and intended to carry the compass needle shown in Fig. 147. DD is a flat coil that has been made by wrapping 3 metres of silk- or cotton-covered copper wire (size 20) round a cylinder (a glass beaker) about 10 cm. in

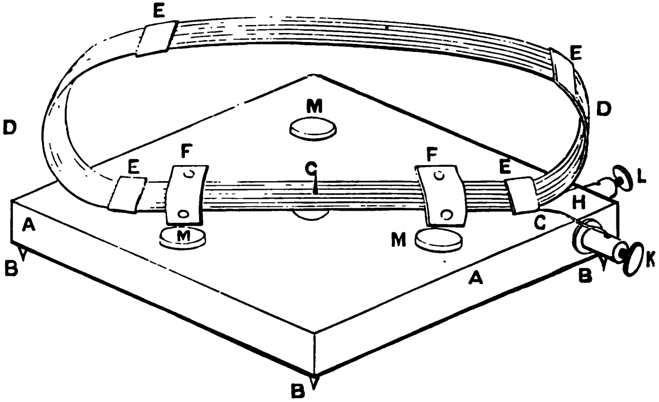

FIG. 146

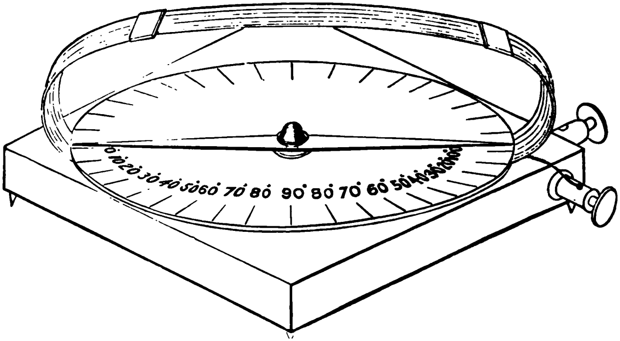

FIG. 147.

diameter. The coil is stiffened, and the strands kept in place by pieces of stout plaster, E, E, E, E, and is fastened down to the block, in the position shown, by two strips of sheet zinc, F F, and copper nails. The ends of the coil, G and H, lead to two binding screws, K and L, with which they are in close metallic contact. M M M are little discs of cork glued to the wood, and to which in turn is glued the disc of card shown in Fig. 147, which is graduated in degrees round the edge, from 0° to 90° in each quadrant, in the manner there indicated in two quadrants. A chink is easily made by separating the strands of the coil a little, to allow of the ends of the needle being seen when it is directly under the coil.

**General Remarks.**—In all experiments in current electricity, whenever the current is required to pass from one piece of metal to another, *e.g.* from one wire to another, care must be taken that the metals are clean, bright, and dry, and firmly pressed together at the point of contact. Hence the ends of wires should be rubbed with sand-paper or emery-paper before putting on a binding screw, and the ends of the binding screw should be similarly rubbed or filed.

In any cell that you are likely to use one terminal or electrode will be made of Zinc, and will be attacked by the liquid of the cell; the other may be of Copper or Carbon, or Platinum or some other substance, according to circumstances, and will not be attacked by the liquid. In any such cell the current is regarded as flowing from the zinc (the anode) through the liquid of the cell to the other electrode (the cathode), so that when the circuit is completed the current enters the cell at the zinc terminal and leaves it by the other.

EXPERIMENT 1.—*First Preliminary Experiment to explain the principle of the galvanoscope.*

*Instructions.*—Connect the poles of a cell[1] by a covered known, let it be found by the hydrostatical method referred to in the last Experiment. Then let a piece, not less than a metre long, of each be measured, and the ratio of the resistances be found. It is best so to choose the lengths that the resistance of one piece is nearly equal to that of the other. Thus, if you find on trial that the resistance of the wire of one metal (A) is very much greater than that of the other metal (B), you should use a greater length of (B) or a shorter length of (A), but not shorter than a metre.

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[1] A granular carbon (Clark) cell is a convenient one to use in these experiments.

**Example.**—The following is an example of an experiment to compare the specific resistance of a certain metal (M) with that of copper.

By means of Wheatstone's Bridge, the resistance of a wire (A) of the metal in question, 2 metres long and ·02 inch thick, was compared with that of a copper wire (B) 6 metres long and ·012 inch thick.

$$\text{(i.)}\ \frac{\text{Resistance of A}}{\text{Resistance of B}}=\frac{28{\cdot}4}{21{\cdot}6}=1{\cdot}32$$

$$\text{(ii.)}\ \frac{\text{Resistance of A}}{\text{Resistance of B}}=\frac{28{\cdot}9}{21{\cdot}1}=1{\cdot}37$$

$$\text{Mean}=1{\cdot}345.$$

∴ Resistance of 2 m. of (A) = resistance of 6 m. of (B) × 1·345
" " 1 " (A) = resistance of 6 m. of (B) × 1·345 × $\frac{1}{2}$
∴ Resistance of 1 " (A) = resistance of 1 m. of (B) × 1·345 × $\frac{6}{2}$
= resistance of 1 m. of (B) × 1·345 × 3.

If B had been chosen of the same thickness as A, its thickness would have been greater in the ratio of ·012 to ·02, *i.e.* ·006 to ·01,

∴ its cross-section would have been greater in the ratio of $\cdot006^2$ to $\cdot01^2$, *i.e.* of ·000036 to ·0001, *i.e.* of 3·6 to 100,

∴ its resistance would have been less in the same proportion,

∴ resistance of 1 m. of wire of metal M = resistance of 1 m. of copper wire of same thickness $\times 1{\cdot}345\times 3\times\frac{100}{36}$

$$\text{or}\ \frac{\text{specific resistance of metal M}}{\text{specific resistance of copper}}=1{\cdot}345\times 3\times\frac{100}{36}$$

$$=\frac{1{\cdot}345}{12}$$

$$=11{\cdot}208.$$

sive positions shown in the following figures (Figs. 149-156), in which the wire and the needle are both in the plane of the diagram.

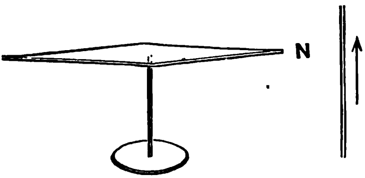


Fig. 149.

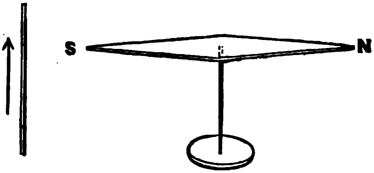


Fig. 150.

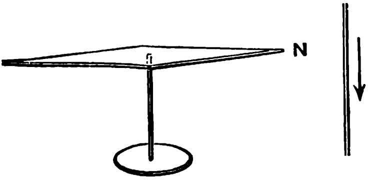


Fig. 151.

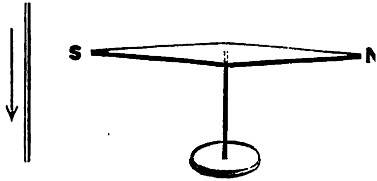


Fig. 152.

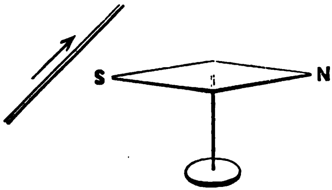


Fig. 153.

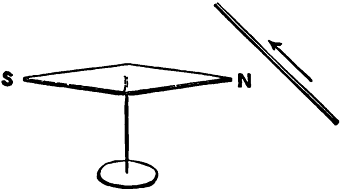


Fig. 154.

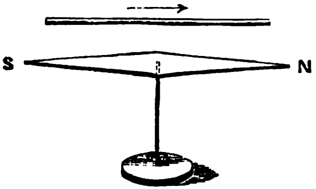


Fig. 155.

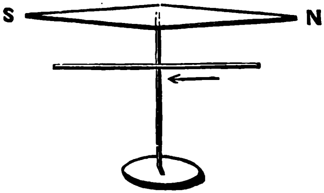


Fig. 156.

substitute a short thick copper wire whose resistance is inappreciable. This will increase the current and the deflection. Now insert rheocord resistance, till the deflection is again reduced to the original value. Observe and record the amount of rheocord resistance necessary to produce this result; this gives you the resistance of wire No. 1.

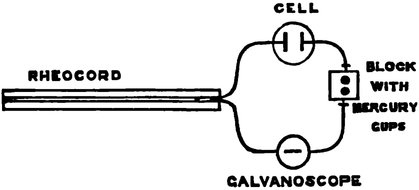


FIG. 164.

Now repeat the experiment in precisely the same manner with wire No. 2.

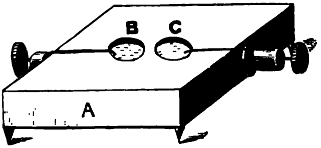


FIG. 165.

A convenient form of mercury cups for this and other experiments is shown in the diagram (Fig. 165).

A is a wooden block, provided with sharp little spikes to fix it to the table wherever it is placed; and in it are bored two hollows, B and C, each about ½ inch wide and ½ inch deep, which hold the mercury. The mercury in each is connected by a thick copper wire with one of the binding screws.

EXPERIMENT 11.—*To find the resistance of the galvanoscope by the method of Sir William Thomson.*

*Explanation.*—We have seen that when a cell sends a *current* through a divided circuit, such as ACB and ADB, as magnetic meridian, *i.e.* in the same plane as the needle, and the ends of the circuit connected with the binding screws.

It is evident that the instrument can only be used to indicate, and not to measure, the currents sent through it, for though the deviation produced by a stronger current will always be greater than that produced by a weaker, the deflection of the needle will not be twice as great when the current is twice as great.

**Wheatstone's Bridge.**—An electric current always flows from a place of higher electrical level or potential to one of lower level or potential, so that if a current flows along a conductor from A to B, we know that A must be at a higher potential than B. Also, as we pass along the conductor from B to A, we pass from points of lower to points of higher level. If the conductor is a wire of uniform resistance throughout, then the potential, as we pass up it from B to A, will rise uniformly. At a point half way between B and A the potential will have a value exactly midway between that at B and that at A. At a point nearer A the potential will be more nearly that at A than that at B. Now suppose the points A and B of the wire AHB to be joined by a second uniform wire AGB. The same is true of the second wire also.

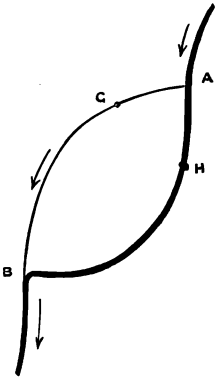


Fig. 160.

At a point G, say one-third of the distance between A and B measured along AGB, the potential will be the same as at a *point H, one-third* of the distance measured along AHB;

consequently, if we join G and H by a wire, no current will flow through it, for currents only flow from higher level to lower, and not between places of the same potential. If, therefore, we connect one end of the galvanometer wire with any point G in one branch, we can find the corresponding point H in the other by moving the other end of the galvanometer wire along the branch till we find a point where no current passes. When the point H is found, we know that the resistance AG is to the resistance GB in the same proportion that the resistance AH is to the resistance HB. Also, if the ends of the galvanometer wire were, to begin with, fixed, as in Fig. 161, but we could move the battery wire A along the wire between G and H, we could find a position for A such that no current could flow through the galvanometer, and then we should know that the resistance AG was to the resistance GB as the resistance AH was to the resistance HB.

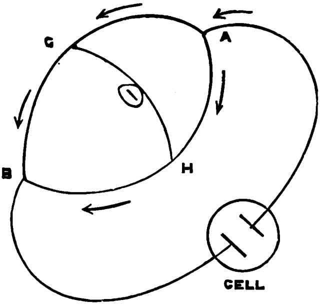


Fig. 161.

In Fig. 161 the galvanometer wire is drawn nearly straight, and the line GAH is curved, but the latter might be straight and the other curved, and then the figure would resemble that of the next diagram (Fig. 162). As before, if we make the contact A in *such a place* that AG is to GB as AH to HB, or, what is

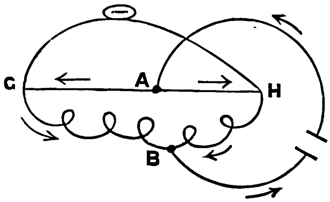


Fig. 162.

the same thing, HA to AG as HB to BG, then no current will flow.

You will now be able to understand the apparatus[1] given you, and shown in the accompanying figure (Fig. 163).

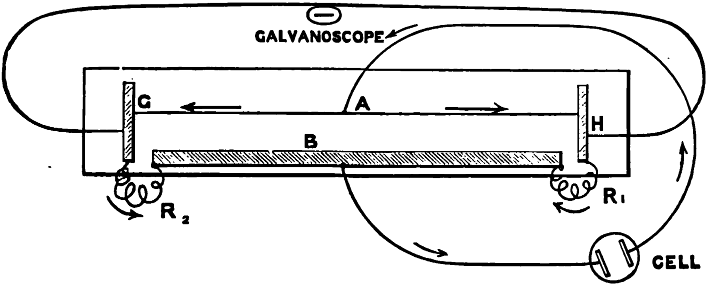


Fig. 163.

The letters correspond to those of the previous figures. The points BG and H are replaced by thick strips of copper, each of which may be regarded as having no resistance.

**Use of the Bridge.**—Suppose that it is required to compare the resistance of a wire $R_1$ with that of a wire $R_2$.

It is necessary to connect them as in the figure, and to find by trial the position of A, for when contact is made there, no current flows through the galvanometer.

When you have found it, you know that $R_1$ is to $R_2$ as AH is to AG.

---

[1] This is the Wheatstone's Bridge described in Guthrie's *Magnetism and Electricity*, Appendix A. It is an advantage to arm the underside of the board with little spikes, in the same way that the galvanoscope block is armed, to prevent it slipping.

Should the whole resistance at command be insufficient to reduce the deflection to a few degrees, the cell itself may be short-circuited by a shunt wire which deviates the greater part of the current. A useful form of resistance, which can be varied between wide limits, is a box of carbon plates, which can be more or less tightly compressed by a screw so as to alter the resistance of the contacts.

You will now be able to understand the following experiment, in which, by means of suitable shunts, the process is conducted without the use of a greater variable resistance than that afforded by your rheocord.

EXPERIMENT 13.—*To calibrate the galvanoscope,* i.e. *to find the value of its indications.*

*Instructions.*—Make the arrangement of apparatus shown in the diagram (Fig. 168).

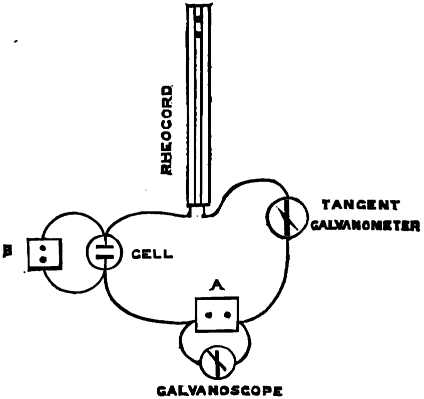


FIG. 168.

A and B are mercury cups. If neither pair is joined, then the current passes from the cell to the rheocord, and through as much resistance as is there interposed, thence round the tangent galvanometer and the galvanoscope, and so back to the cell. If the mercury cups B are joined by a short thick wire of small resistance, then the greater part of the current will be shunted or "short-circuited" through the mercury cups, and only a small proportion will pass round the instruments. This proportion will remain the same so long as the shunt wire is the same. If the short thick shunt wire be exchanged for a long thin one of greater resistance, then a larger proportion of the current will pass through the instruments. Thus the mercury cups B afford a convenient means of regulating the strength of the current passing round the galvanometer and galvanoscope. By varying the rheocord resistance we can also regulate the current passing round the circuit. Again, by joining the cups A by a shunt of suitable resistance, we can deviate as much as we like of the total current from the galvanoscope.

To begin with, let such shunts be used at A and B that when the whole rheocord resistance is interposed the galvanoscope deflection is about 5°, and the galvanometer deflection not more than 10°. Observe and record the reading of each. Then reduce the rheocord resistance till the galvanoscope deflection is 10°, and again note the deflection of the tangent galvanometer. Proceed in this way, noting the galvanometer deflection that corresponds to readings of 15°, 20°, 25°, of the galvanoscope up to 45°. If you should find that the rheocord resistance is reduced to zero before a deflection of 45° is reached, then you may increase the current by interposing a greater resistance between the mercury cups B, or, if no shunt has been used there, then the shunt at A may be replaced by one of greater resistance; but, in this case, the observation for the last galvanoscope deflection observed must be repeated with the new shunt, in order that we may be able to connect the observations made before the change with those made after it.

The following is the record of an experiment made in the way described, from which the method of using the results will be understood.

*Example of the Calibration of a Galvanoscope.*

| Galvanoscope Deflection. | Tangent Galvanometer Deflection. | Tangent of the angle of deflection in the Galvanometer. |
|---|---|---|
| 6° | 6°·50 | ·1139 |
| 10° | 11° | ·1944 |
| 15° | 17° | ·3057 |
| 20° | 22°·5 | ·4142 |
| 24° | 28° | ·5137 |

Here the galvanoscope shunt was exchanged for one of greater resistance, with which the last observation was repeated.

| Galvanoscope Deflection. | Tangent Galvanometer Deflection. | Tangent of the angle of deflection in the Galvanometer. |
|---|---|---|
| 24° | 9°·7 | ·1712 |
| 30° | 12°·5 | ·2217 |
| 40° | 20°·5 | ·3739 |
| 45° | 26° | ·4877 |

The current strength is in each case proportional to, and is measured by, the tangent of the galvanometer deflection, which is looked out in a table of tangents, and given in the third column. The effect of the change of shunt has been to cause a current, producing in the galvanoscope a deflection of 24°, and whose strength was previously represented by the number ·5137, to be represented by the number ·1712, which is exactly three times smaller; hence to make the two series continuous, we must multiply the last four numbers of the last column by 3.

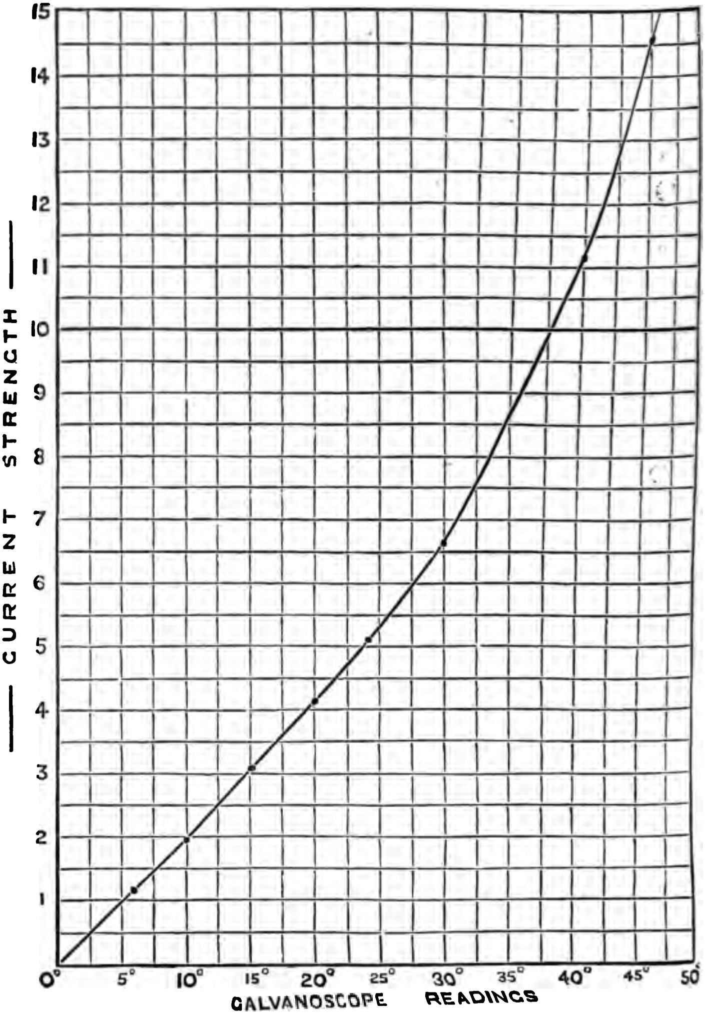
Thus we obtain the following table:—

| Galvanoscope Deflection. | Current Strength. |
|---|---|
| 6° | ·1139 |
| 10° | ·1944 |
| 15° | ·3057 |
| 20° | ·4142 |
| 24° | ·5137 |
| 30° | ·6651 |
| 40° | 1·1217 |
| 45° | 1·4631 |

We may, for convenience, consider the values in the second column to be multiplied by 10, and from the results construct the curve of the accompanying diagram (Fig. 169), which will enable us at any future time to find the current strength corresponding to any direction of the galvanoscope.

It must be remembered that the calibration curve will no longer apply if the galvanoscope coil is displaced or bent, and it is well to protect it from accidental knocks by fixing over it one or two arches of stout brass or copper wire. Also it is to be noticed that the calibration curve will probably not apply for deviations of the needle in any other quadrant, since the needle is probably not quite symmetrically placed within the coil. Hence, when the instrument is to be used for *measuring* currents, care should be taken that the deflection of the needle is observed in the quadrant to which the calibration *curve applies*.

GALVANOSCOPE CALIBRATION CURVE.



EXPERIMENT 14.—*To find the internal resistance of a cell.*

*Instructions.*—Connect the cell by means of short thick wires, with the galvanoscope and the rheocord, interposing at first no rheocord resistance. Observe the deflection $(D_1)$ of the needle. Find by the calibration curve what current this corresponds to. Find next by the curve what deflection $(D_2)$ would correspond to half this current. Insert rheocord resistance till this deflection is indicated by the needle. The current is now half what it was. Therefore the resistance of the circuit has been doubled. Therefore the resistance added equals the original resistance of the circuit. Subtract from this the known resistance of the galvanometer (that of the connecting wires may be neglected), and the remainder is the resistance of the cell (the unit of resistance being that of unit length of the rheocord wire).

The method assumes that the electro-motive force of the cell remains constant throughout the experiment, but in most cells the polarisation increases with the current strength, and diminishes the effective electro-motive force.

The value obtained in this way should be compared with that obtained by Mance's method (Experiment 12).

EXPERIMENT 15.—*To compare the electromotive force of two cells of different kinds. 1st Method.*

*Instructions.*—Arrange the two cells in circuit with the galvanoscope first, so that the currents from each are in the same direction, and then so that the currents from each are in *opposite directions*, and observe the deflections $(D_1$ and $D_2)$

in each case. Then find, by the calibration curve, the corresponding currents ($C_1$ and $C_2$) in each case.

The resistance of the circuit is the same in the two cases, being the resistance of each cell *plus* the resistance of the galvanoscope and connections; while the electromotive force in the first case is the sum of the electromotive forces of the two cells or $E_1+E_2$, while, in the second case, it is the difference $E_1-E_2$; therefore, calling the total resistance R,

$$\therefore \frac{E_1+E_2}{R}=C_1$$

$$\frac{E_1-E_2}{R}=C_2$$

$$\therefore E_1+E_2=RC_1$$

$$E_1-E_2=RC_2$$

$$\therefore \frac{E_1+E_2}{E_1-E_2}=\frac{C_1}{C_2}$$

$$\therefore E_1+E_2=E_1\times\frac{C_1}{C_2}-E_2\times\frac{C_1}{C_2}$$

$$\therefore E_1\left(1-\frac{C_1}{C_2}\right)=-E_2\left(1+\frac{C_1}{C_2}\right)$$

$$\text{or } \frac{E_1}{E_2}=\frac{\frac{C_1}{C_2}+1}{\frac{C_1}{C_2}-1}.$$

It may happen that the current sent first when both cells work together is too strong, and deviates the galvanoscope needle beyond the point to which the calibration extends. Should this be the case, a shunt must be used with the galvanometer, which must be kept in its place while the second measure is made.

EXPERIMENT 16.—*To compare the electromotive force of two cells of different kinds. 2nd Method.*

*Instructions.*—First find the internal resistances ($R_1$ and $R_2$) of each cell (either by the method of Experiment 12 or of Experiment 14). Then connect with the galvanoscope and the rheocord, and observe the deflection.

Now exchange this cell for the other, and alter the rheocord resistance till the current is the same as before. The galvanoscope resistance being known, as well as the resistance of the cell, and the rheocord resistance in each case, you know the total resistance ($R_1$ and $R_2$) in each case.

Therefore, since $\frac{E_1}{R_1}$ = current,

and $\frac{E_2}{R_2}$ = same current,

$$\frac{E_1}{R_1}=\frac{E_2}{R_2},$$

$$\text{or } \frac{E_1}{E_2}=\frac{R_1}{R_2}.$$

**Reminder.**—The student should understand that the experiments he has made, though they will have helped to familiarise him with the principles involved in many electrical determinations, give no idea of the precision of modern electrical measurements, or of the many considerations requisite to secure the most accurate results.

# APPENDIX.

# APPENDIX.

## LIST OF APPARATUS REQUIRED FOR THE COURSE.

In addition to the fixtures alluded to in the Introduction, the laboratory should contain a *blackboard*, a *Fletcher's gas-burner*, and a *large tin kettle;* also a supply of *methylated spirits of wine*, *turpentine*, and *mercury*.

The following apparatus, being in constant demand for all kinds of experiments, should be kept in the cupboards under the work-tables, as the permanent stock of the table :—

1. A metre and half-metre rule of boxwood, divided to millimetres (such as is supplied by Messrs. Rabone and Sons, Hockley, Birmingham).
2. A balance in a box and set of gram weights, ranging from ·05 grams to 1000 grams. (A very useful balance is the so-called Australian Gold Scales, 8-inch beam, No. 135 B in the Catalogue of Messrs. Day and Millward, Suffolk Street, Birmingham, price 4s.)

   A set of gram weights, ranging from 1 gram to 100 grams, can be obtained for 3s. 6d. The heavier weights are usually of iron, and will require a good deal of trimming down to make them correct. The smaller weights should be kept in a box, with a place for each, and a pair of tweezers for handling them.
3. A wooden staff with a projecting arm of stout wire, to be fitted upright in a hole bored in the table-top, for hanging the balance.
4. An iron retort-stand with three rings and two clips.
5. A large pair of scissors.
6. *A pair of compasses.*

7. Three or four test-tubes of different sizes, the largest being at least 1¼ inch wide.
8. A boxwood sphere about 1½ inch in diameter.
9. Three thin glass beakers of different sizes, the smallest just large enough to admit the wooden sphere, and the largest of about 500 cub. cm. capacity.
10. A cardboard tray, 1 foot × 8 inches—useful for experiments with mercury, and for holding small objects.
11. Two cylinders, accurately turned, one of copper and one of iron, each 1¼ inch long × ⅝ inch in diameter.
12. A triangular file and a round file.
13. A pair of cutting-pliers.
14. A test-tube clip.
15. A Bunsen burner.
16. A few pieces of narrow glass tubing.
17. Two watch-glasses.
18. A large pill-box full of shot.
19. A ball of soft string.
20. A reel of strong cotton.
21. Two square feet of stout cardboard.
22. A paper of stout pins.
23. Four blocks of planed deal, 5 inches square and 1 inch thick; also two blocks of the same area, but only ½ inch thick.
24. A rectangular block of hard wood, about 2 inches square and 1 inch thick.
25. A right prism of hard wood, with triangular ends, the sides of the triangles being 3 inches, 2½ inches, and 2 inches respectively, and the height of the prism 2 inches.
26. A cylindrical tin vessel, about 3 inches in diameter and 4 inches high, not turned over at the edge.
27. Two feet of black india-rubber gas tubing.
28. A supply of foolscap paper.

In addition to the permanent apparatus just mentioned, the following will be wanted for the experiments in the respective subjects under which they are classified. Of those items marked with an asterisk only a small quantity will be required for a class of thirty boys.

## MENSURATION.

*1. Opisometer, as described in Exercise 4.
2. Specific-gravity flask.
*3. Cylindrical case made of roll of paraffined paper (as described in Experiment 19).
4. A pebble.
5. Crystal of copper sulphate about as large as a man's thumb.
*6. Saturated solution of copper sulphate.

## HYDROSTATICS.

1. A U-tube, as described in Experiment 1.
2. A V-tube for Experiment 2.
*3. An india-rubber T-tube, for Experiment 3.
*4. Saturated solution of common salt.

Waterproof case for the copper cylinder, easily made by rolling paper round the cylinder, and then filling up the end with melted paraffin or plaster of Paris. The whole may be rendered waterproof by dipping in melted paraffin.

5. Large glass stopper.
6. Six metres of copper wire, size No. 20.
7. Two uncut lead pencils.
*8. A tall narrow gas jar.
9. A piece of sheet india-rubber—the piece used for the Electrophorus (see apparatus for Statical Electricity) will do very well.

## BAROMETER AND BOYLE'S LAW.

1. Small glass funnel.
2. Manometer made of bent glass tube, about 2½ to 3 metres long, the short leg, which is closed, being about 30 cm. long. The tube should be of very uniform bore towards the closed end.
3. Small porcelain mortar.
4. *Barometer tube,* at least 96 cm. long, and of uniform bore.

## MECHANICS.

1. Two large pill-boxes.
2. 1 lb. of large shot.
3. A metre or two of thin square india-rubber cord, about 1 mm. thick.
4. An india-rubber ring.
5. A few pins.

### *Centre of Gravity.*

1. Plumb-line made with a thread and bit of lead.
2. A piece of stout copper wire (size 16, say), 2 feet long.

### *Friction—Inclined Plane—Friction of Cords and Pulleys.*

1. A writing-slate with the frame removed.
*2. A hammer.
3. Some iron tacks.
4. A metre or so of india-rubber cord of two or three sizes, ranging from about 1 mm. to about 3 mm. thick.
5. A strip of window glass 1 foot long by 6 inches wide.
6. A little olive oil.
7. A pulley, made as described in Experiment 32.
8. Some small corks.

## ELASTICITY.

1. An additional triangular file.
2. Three laths of the same well-seasoned flexible wood (*e.g.* lime) each 40 inches long and 1 inch wide, and accurately planed: one $\frac{1}{8}$ inch thick; one $\frac{1}{4}$ inch thick; and one $\frac{5}{16}$ inch thick. Also a fourth lath of the same wood, 40 inches long, $\frac{1}{4}$ inch thick, and 2 inches wide.
3. A closely coiled spiral spring, 1 foot long and $\frac{1}{4}$ inch in diameter, made of steel wire (size 24, say), each end turned up into a central hook.
4. A steel wire 1 to 2 metres long (size 26).

5. A tuning-fork.
6. A little wedge of hard wood, shaped as shown in Fig. 92, 7 inches long, $\frac{1}{10}$ inch thick, $\frac{1}{3}$ inch wide at thick end, and $\frac{1}{8}$ inch wide at thin end.

### *Simple Pendulum.*

No additional apparatus.

## HEAT.

1. 1 foot of copper wire (size 16).
2. „ „ „ (size 21).
3. „ iron „ „
*4. Large Bunsen burner.
5. Centigrade thermometer (paper scale, reading to 100°, or better, 150° C.).
6. One 3-oz. glass flask with wide neck.
7. Two 4-oz. glass flasks.
8. Ice.
9. Variety of corks.
*10. Set of cork-borers.
11. Wire gauze to cover large ring of retort-stand.
12. Rectangular block, 5 inches square, $\frac{1}{2}$ inch thick, with hole in middle to admit a cork.
13. Large beaker 4 to 5 inches in diameter.
14. Sheet of tinfoil.
15. Paraffin candle of good quality.
16. Two *thin* glass beakers, each 500 to 600 cub. cm. capacity.
17. A cylindrical vessel of very thin brass—such as is used for the thinnest stencil plates,—3 inches high, $1\frac{1}{2}$ inches in diameter.
18. 100 grams of thin copper wire cut up into very short bits, not more than 1 cm. long.
19. A packet of very small iron tacks, also about 100 grams each of sheet lead and sheet zinc, cut into very small pieces.
*20. Large flat cork.*

21. 6 oz. of ammonium nitrate.
22. Thin glass flask with wide neck about 600 cub. cm. capacity.
23. 1 foot of narrow black india-rubber connecting-tube.
24. A piece of thick glass tube, 6 inches long, ⅝ inch internal diameter to be fitted as described in Experiment 33, p. 190.
25 2 feet of narrow glass tubing.
26. India-rubber stopper to fit the large test-tube, perforated with a hole in which the thermometer will fit air-tight.

## MAGNETISM.

1. Two bar magnets made of tool steel, about 9 inches long, ¼ inch thick, and ½ inch wide.

   (*N.B.*—The magnets of the whole class should be re-magnetised from time to time on a strong electro-magnet.)

2. Some iron nails and tacks of different sizes, including two very large nails to serve as armatures; also a few French wire nails.
3. A large pill-box full of fine iron filings.
4. Piece of fishing-gut, 3 feet long.
5. Protractor.
6. Two gummed labels.
7. Darning-needle.
8. Compass needle, 2 to 3 inches long.
9. Half a dozen thin steel knitting-needles.

*10. Petroleum.

11. Some unspun silk.
12. Blotting-paper.
13. An ounce of tannin.
14. A lump of beeswax.

*15. A hammer.

## STATICAL ELECTRICITY.

1. Four ebonite stirring rods, each 10 or 12 inches long; two of them at least ⅓ inch thick.
2. A piece of good flannel, 1 foot square.
3. A piece of thin black silk stuff, 2 feet by 1 foot.

4. Two glass rods, 12 or 15 inches long, and ½ inch thick.
5. Two sticks of good sealing-wax.
6. A foot of copper wire (size 20, say).
7. Four good-sized pith balls in a pill-box.
8. A few yards of white silk embroidery thread.
9. Small deep metal vessel (*e.g.* the calorimeter described under head of Heat, No. 17).
10. Pair of india-rubber finger-stalls.
11. Lump of beeswax.
12. Gold leaf electroscope, made as described on page 255.

*13. Gold-beater's pad, knife, and tip, for manipulating gold leaf.

(The method of using these may be easily learned by the teacher from a gold-beater.)

14. Small slab of ebonite, 1 or 2 inches square, and ½ inch thick.
15. Disc of tinned iron, 6 inches in diameter, with smooth edge, to serve as an electroscope plate, with small socket soldered at the back to admit a stout ebonite, as handle.
16. Square of vulcanised sheet india-rubber 7 or 8 inches in the side.
17. Two pill-boxes, one full of shot.
18. A sheet of tinfoil.
19. Piece of wire gauze, 2 feet by 1 foot.
20. Packet of fine sewing-needles.

## CURRENT ELECTRICITY.

1. Galvanoscope, made as described on p. 273 *et seq.*
2. A Clark's granular carbon cell.
3. A Daniell cell (or a Bunsen cell).
4. A 2¼-inch compass needle.
5. A darning-needle and one or two fine sewing-needles.
6. 10 yards of No. 20 cotton-covered copper wire.
   „ 26 „ „
   2 „ 26 German-silver wire.
   2 metres of platinum wire, size 30.
7. Wheatstone's Bridge, constructed in the manner described in Professor Guthrie's *Magnetism and Electricity, Appendix A.*

8. A rheocord of German-silver wire, constructed in the manner there described.
*9. Tangent galvanometer.
10. A square foot of millimetre curve paper.
11. A block, bored and fitted for mercury cups, as described on p. 286.
12. 6 binding screws for joining the ends of wires.
13. 6 terminals, such as those shown in Figs. 146 and 147.

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